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Doctorate of Philosophy in
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XXIV cycle

Ph.D. Thesis in

Decision Support Systems for Sustainable Plant Design

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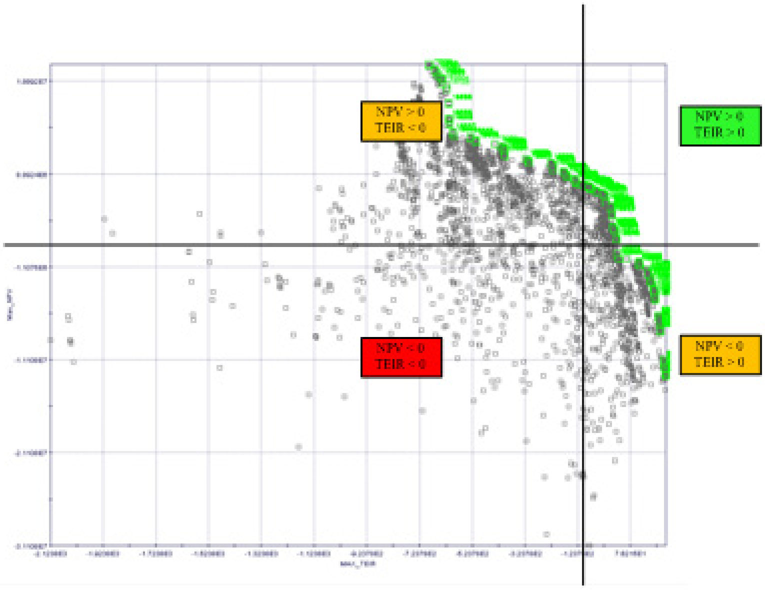

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Figure in the cover page:
Pareto-Front analysis for Economic and Environmental Impact Design of a CHP plant, maximizing both Net Present Value (NPV) and Total Emission Impact Reduction (TIER)

Summary

In this work some innovative aspects of energy plants design have been treated. Specifically, the main objective of the study consists in providing a methodology for supporting the decision making process, aimed to a *sustainable* design of such plants. Territoriality and multi-criteriality are at the basis of this model. Referring to the former, the described model provides an effective method for design locally sustainable Combined Heating and Power (CHP) plants, focusing on the actual emissions of the proposed system in terms of NO_x, CO, PM, NMVOC and SO_x emissions, avoiding the common mistake to focus on the unique – and often misleading – parameter of greenhouse-gases emissions. Furthermore, the model presents an interdisciplinary approach – multi-objective and multicriteria – in which the traditional opposition between economic and environmental objective is treated considering the approaches of Multi-Objective Analysis, while the need of including qualitative factors in the decision making process is done afterwards by using the Analytic Hierarchy Process (AHP) multi-criteria method, aimed to identify the *better* solution among the various feasible alternatives. This approach has been applied to various and diversificate case studies, such as regional planning of Friuli Venezia Giulia Region (Italy), facility management in the health-care industry, manufacturing industry in the province of Pordenone (Italy) and an Industrial Area located in Perth (Western Australia).

KEYWORDS: sustainability, Decision Support System, multi-objective, multi-attribute

Preface

Sustainable development policies represent a global address that currently have been considered in various and different contexts, from civil to industrial approaches, with multiples shades related to the so-called "three pillars" (Adams, 2006) of sustainable development, that is:

1. Economic Development;
2. Environmental Development;
3. Social Development.

However, on an institutional level, policies and directives of various councils of UN, EU and national bodies, are often related to only one of those aspects, treating them in an independent way, limiting and opposing their effects, as it appears evident by the opposition between environmental impact reduction policies and economic development. In the field of energy plant design, causality between pollutants emission reduction and costs increment is undeniable for most of the cases, but such intrinsic opposition between these two objectives has been treated by most of the authors in an exclusive way, considering independently one aspect or the other.

Furthermore, in this context, the concept of *environmental impact* is all but clear. From both designer and client, it is often limited as a "*fossil fuel consumption*" or "*CO_2 emissions*", while the requests of the regulator are related to a far more large spectrum of pollutants such as oxides of Nitrogen (NO_x) and sulphur (SO_x), dusts (PM10 and PM2.5) and carbon monoxide(CO). Furthermore, those pollutants are related to a number of impacts (acidification, climate change, smog, etc), whose relative specific weight is a far-than-clear concept. Social aspect, eventually, is difficult to measure because of its own nature, linking most of the times to subjective judgments necessarily related to the specific case study, and later on quantified by common socio-descriptive tools. Neglecting such aspect, in all the stages of plant lifecycle, would be a limit, given that most of the times it often represents a determining factor of the whole decisional process.

Territoriality and multi-criteriality represent two key elements of this work, which presents the main objective to provide an innovative, bottom-up, methodology for supporting the decision making process, aimed to a sustainable design of energy plants. The methods are to be applied to real cases, whose main scope is related to energy plant design in manufacturing or particularly-relevant civil sectors.

The decision making process will follow a traditional "horizontal" path. Starting from a primary stage of data/information collection ("intelligence phase"), a synthetic stage is to be done for feasible alternatives' identification ("design phase"), aimed towards a final process of choosing the *better* trade-off alternative ("choice phase") related to the specific decision making process assessed.

Each of those steps presents specific secondary objectives. The intelligence phase aims to identify analytical methodologies, software-assisted, in order to facilitate and ease the approach of the decisor maker to the problem to be solved. Particularly, this work will focus on indicator approach, which represents a simple but effective way to identify priorities. The second *creative* stage aims to identify and utilize the tools of traditional Multi-Objective Analysis (MOA) in the field of energy plants design. Specifically, the reference software for MOA (Esteco^{TM} ModeFrontier 4.3 has been used, supported by the flexibility and ease-of-use of Microsoft^{TM} Excel. Eventually, the third last *synthetic* stage is required in order to include the “social” variable into the decision making process, finalizing the triple viewpoint of the very concept of Sustainable Development. Analytic Hierarchy/Network Process (AHP/ANP), as proposed by Saaty (1981), has been chosen as a reference method for such goal.

This works is made up of two main sections. In part I the foundations of the DSS proposed will be assessed. Chapter 1 will assess the evolution of the concepts of Sustainable Development, particularly emphasizing the role of industrial development and the methodologies for multi-criteria assessment in literature. Chapter 2, coherently with the three pillars of sustainability previously described, will provide a multi-disciplinary approach of a particular category of energy production technologies, i.e. Combined Heating and Power (CHP) plants, providing a multi-disciplinary analysis of economic, technological and environmental performances. Chapter 3 will present the DSS model, focusing on the three-step approach previously described.

Applications of such DSS are the main objective of section II. Chapter 4 presents an application of the DSS to territorial planning in the food-industry of the Friuli Venezia Giulia region (Italy). In chapter 5 the methodology has been used for assessing and identifying energy savings opportunities in the health-care industry of the same region. Manufacturing industry of the Pordenone province (Italy) is the object of chapter 6, which presents the results of a survey over 35 companies located in the Pordenone municipality. Eventually, the last case study – chapter 7 – refers to an industrial area located in Perth, Western Australia, after a short-term collaboration with the “Centre for Sustainable Engineering (Curtin University of Technology, Perth, Western Australia) developed during the PhD. studies.

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Part I

Theory and Methods

1

Introduction

This first chapter is structured in order to outline the general principles guiding the Decision Support System (DSS) to be developed. Coherently with the scope of the work, this chapter will provide a framework and the basic theories of:

- Sustainable Development;
- Industrial Ecology;
- Multi-Criteria Decision Making.

From the basic concepts behind the policy of sustainable development, which will be reviewed following the temporal progression of International, European and National policies, the focus will shift towards the industrial aspects of such policies, leading to the second major area of Industrial Ecology. Such relatively new scientific discipline will be analyzed in its main principles and tools. Having noted the relevance of multidisciplinary approach to the area, a literature analysis of some methodologies for Multi-Criteria Decision Making will be carried out.

Before introducing such topics, some of the most relevant and up-to-date (2011) statistics will be reported, referring to the social, economic and environmental aspects of the themes to be treated in this work, eventually combined in mixed statistics, later referred to the industrial sector.

1.1 Sustainability and Development: Statistics

Socio-economic context and energy-environmental data are variables absolutely correlated, and an assessment of the former can’t neglect the latter. In this section some relevant statistics related to the objective and the scope of this study will be assessed, particularly referring to energy consumption and pollutants emissions data, correlating these values with economic and/or demographic parameters. The assessment will be tailored to the industrial field in order to quantitatively contextualize the assessment which will be provided later on.

Referring to socio-economic context, in the last 10 years, the average yearly GDP growth of the EU-zone (Eurostat, 2010) has been limited to about 2% - compared to an average global value of 3.1% (UN, 2011) with a positive peak of 3.3% (2006) and a negative fall-out correspondingly to the economic/financial crises of 2009 (-4-3%). Demographic trend of EU shows an increase in population, from 480 million in 2000 to about 500 currently (+4%), but still limited if compared with the global trend (+15% from 6 to about 7 billion, source (US Census, 2010).

Correspondingly, world energy production, during the last 10 years, has shifted from about 10.000 to the current 12.300 Mtoe, (International Energy Agency, 2010), increasing more than 20%. Power consumption, similarly, passed from 15.000 TWh to current 20.000 TWh, increasing more than 30%. Such increase in mainly due to developing countries (mostly BRIC, Brazil, Russia, India and China), while no substantial increase has been recorded in Europe (around 1.700 Mtoe). Fossil and nuclear energy sources comprehend, at a global level, about the 87% of energy sources, the rest being covered by renewable sources.

From the environmental viewpoint, the concentration of greenhouse gases such as carbon dioxide and methane passed from 280 ppm of the pre-industrial period (beginning of ‘70) to the 365 ppm of 1998 (average increase of 1.5 ppm yearly, considering CO2 residence time) while the concentration of methane increased even more, 7 ppb yearly, from 700 to 1745, notwithstanding the limited residence time in the atmosphere of methane, compared to the CO_2 (12 vs. 200 years) (IPCC, 2001). The presumed correlation between anthropic activities (GHGs emissions) and climate change (temperature increase and the so-called “Hockey Stick Graph”) led the way to a series of binding policies for reducing GHG emissions, mainly after the Kyoto Protocol (1997), and many initiatives at a communitarian and/or national level. The objectives of those policies, however, are still far to be achieved.

Correlation between economic, environmental and socio-demographic factors is of major importance when assessing such statistics. For example, on Figure 1.1, GDP, energy consumption and GHGs emissions are reported referring to the last ten-year data. The decoupling (the different slope between the red and the blue line) between GDP’s and energy consumption trend is confirmed, especially for the first years of 2000s, even if the economic crises similarly impacted on both energy consumption and GDP’s growth. However, the common indicator for integrated energy end economic assessment, the “energy intensity” indicator calculated as ratio between energy consumption and GDP showed, from 1998 to 2009, a sensible decrease (17% in EU and 6.6% in Italy) (Eurostat, 2010). GHGs emissions and energy consumption trends are extremely correlated, with the only exemption of 2007-2008 values, decoupled.

Figure 1.1: Trends in GDP, CO2 emissions and energy consumption – EU27

Pollutants emissions policies, furthermore, did not only refer to GHGs gases, but involved a series of pollutants impacting on Ozone depletion, acidificating substances (NO_x and SO_x), dusts and unburnt substances, organic compounds (PAHs, VOCs. International policies addressing such pollutants has led to an-almost total reduction in CFCs consumption and other Ozone Depleting Substances, (ODPs), respectively reduce by 99 e del 73% (UN, 2008), while also NO_x e SO_x reduction, at least related to OECD countries, have been reduced by about 15 and 45% respectively (OECD, 2004).

1.1.1 Manufacturing Industry

Industrial sector, intended as manufacturing on the narrow meaning of the term and thus excluding power generating companies, represents one of the main actors regarding energy consumption and pollutants emissions. In Europe, energy consumption of manufacturing industry accounts about 27% of the total 989 ktep and similar percentages have been reported for GHG’s emissions, about 21% of the total (Eurostat, 2010). Referring to Potentially Acidificating substances (AP), expressed in kilograms of equivalent SO_2, tropospheric-ozone formation potentials (TOFP) and particulate (PM), the relative relevance of manufacturing industry is minor, as the percentages shown on Table 1.1 demonstrate, but it also verified that the reduction trend of such pollutants related to manufacturing companies is strongly reduced when compared to the general trend, (Figure 1.2), and even increasing when referred to dust emissions.

Table 1.1: Manufacturing Industry relevance in pollutants emissions (Eurostat, 2010),

	EU-27	**Italy**
AP	13%	12%
PM	17%	15%
POFP	15%	11%

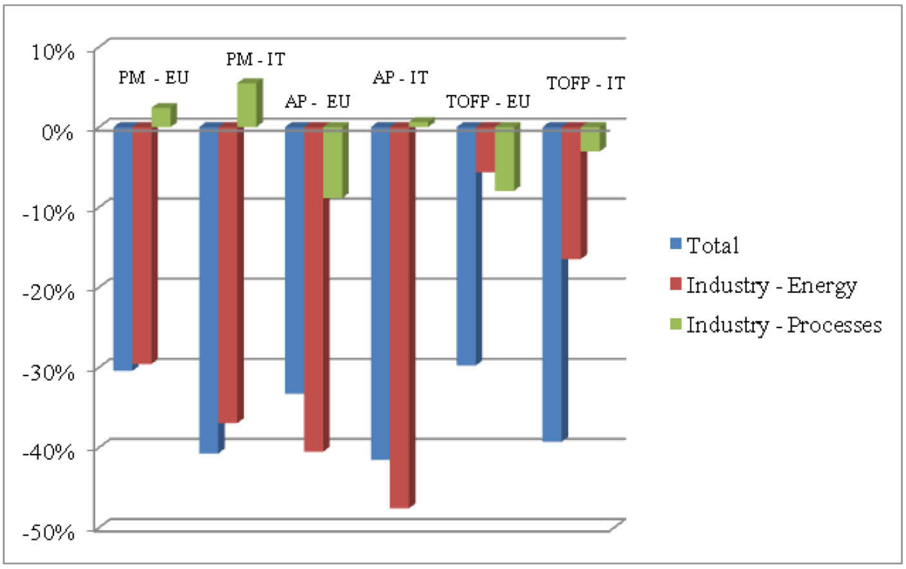

Figure 1.2: Emission trends (1996 – 2007) related to manufacturing industry, (Eurostat, 2010)

Assessing both economic and energy data also provides interesting insights. A broadly-used macro-indicator is the average Brent price (US, EIA, 2011), passed from 15 dollars per barrel of 1994 to the current (July 2011) 108 \$/bbl, with average national import prices (MSE, DGERM, 2011) which presents a completely similar trend, as shown in the following Figure.

Figure 1.3: Brent price - average monthly prices from 1994 to 2011

In the EU, the average energy prices, referring to the industrial sector and excluding the tax component, has shown a sensible increase for both fossil fuels (with natural gas as the most relevant fuel used in the EU) and power prices. Such increases, referring to the 1999 prices and taking the Eurostat data, show that industrial power prices increased of an average 31 and 59% (for the EU-15 and Italy respectively) and a further 12% in the following three years. Natural Gas prices increased even more sensibly, more than doubling its prices from 1999 to 2010 from 3.49 to 7.76 €/GJ (+122%, in EU) and from 3.47 to 7.78 (+124% in Italy). Eventually, the market value of CO_2, whose relevance will be discussed later on this work, ranges from 13 to 17 dollars per ton, as quotated from the three most relevance markets (EEX, 2011), (ICE, 2011) (Powernext, 2011).

1.2 Sustainable Development

"Sustainable Development" (SD)'s breakthrough in policy discussions can be traced in 1987. From that year on, this expression has increasingly taken its place in common policies and practices worldwide. Intuitively, the notion progressively took its space on general debates by means of an increased attention of public and media, dominated by one of its facets – the environmental one – which represents nowadays a matter of daily debates.

The aim of this section is that of highlighting the evolution of international consensus over the main policies and principles of SD, from its first and necessarily general and broader concepts, to the local and tailor-made notions accepted and implemented on local operational levels.

Particularly, this chapter will focus on

- International outlook on Sustainable Development (SD);
- European Union (EU) view on sustainability;
- Italian policies on sustainable development

This section will describe with progressively increasing depth the relevant themes addressed from the international to the national community, in order to highlight the concepts behind sustainable development. The environmental protection aspects of sustainability will be addressed, noting their peculiar relevance into the national policies, while the role of industry in sustainable development policies will also be investigated. Figure 1.4 outlines the main references considered in this chapter for sustainable development assessment, also defining the timeline of the most relevant moments in policy making.

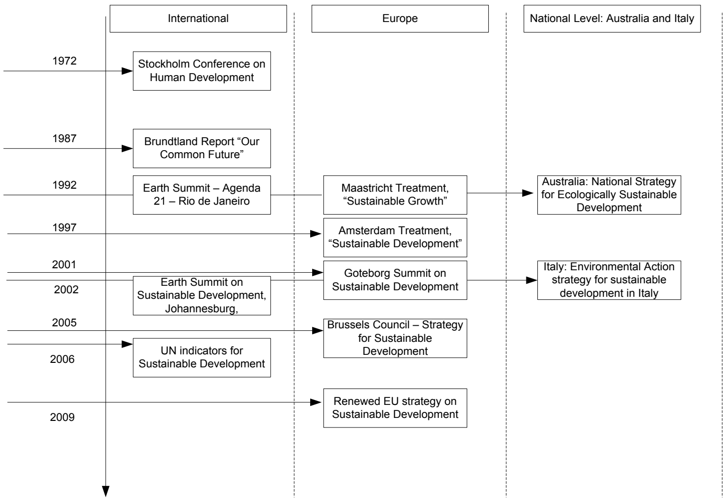

Figure 1.4: Sustainable development: international, European and national policies evolution

1.2.1 Sustainable development: International Outlook

Even if the contribution of man-made actions towards the environment have been recognized since early 60s – the toxicology effects of pesticides were published in 1962 (Carson R., 1962), while the Swedish and the US Environmental Protection Agencies were funded in 1967 and 1969 respectively – the influence of human-made actions over the natural environment found its first international acknowledgment in 1972, with the UN conference held in Stockholm on "Human Environment". Such conference outlined a series of 26 principles, among which the relevance of human responsibility to future generations, together with the importance of state monitoring for pollution prevention, financial and economic intervention, support to developing countries, need of careful planning, technology contribution, education and the need of different standards for developed and developing countries. (UN, 1972). This declaration led to the formation of a sovereign agency (the United Nations Environmental Program, UNEP) to monitor and study the effects of man-made activities on environment, particularly referring to developing countries. Ten years later (1982), a World Commission on Human Environment and Development was established in order to develop a report on various economic, social and environmental issues. The resulted report "Our Common Future" (1987) is considered the seminal work on SD. The same year, the Montreal protocol banned the use of ozone-depleting substances, while on 1988 an International Panel on Climate Change (IPCC) was established to study the effects of pollutants emissions on the natural environment. The following international conference on SD – from now on called "Earth Summit" – particularly relevant for its implications, was held in Rio de Janeiro (1992) and was named 'Agenda for the 21th century', shortened in 'Agenda 21'. In 2000 the UN had included environmental sustainability as one of the eight millennium goals to be achieved before 2015, while the subsequent Earth Summit was held in Johannesburg (2002). Some of these major conferences' outputs will be assessed in the following paragraphs.

1.2.1.1 Our Common Future (1987) – The Brundtldand Report

The Brundtldand report, from the name of the president of the World Commission for Environment and Development, the Norwegian Gro Harlem Brundtland, represents the first relevant step for SD, defined at that occasion as the development which allows present generations to satisfy their needs without compromising future generations' ones to satisfy their own. (WCED, 1987). At the following conference of UN at Nairobi (8,9 June 1987), the UNEP adopts the report named 'Our Common Future' and transmits the acts to the General Assembly, which ratified the document, however lacking of binding prescriptions. The reports highlights that the approach of the commission had necessarily had to be multi-disciplinary, in order to promote a broad participation of the multiple stakeholders involved in the decision making processes. Particular attention has been associated to the correlation between economic/social variables and environmental ones, highlighting that "w*hen the terms of reference of our Commission were originally being discussed in 1982, there were those who wanted its considerations to be limited to "environmental issues" only. This would have been a grave mistake. The environment does not exist as a sphere separate from human actions".* (WCED, 1987)*, pp.13).*

1.2.1.2 Agenda 21: The United Nations Programme of Action from Rio (1992)

Agenda 21 is the action programme for SD signed by the UN after the "Conference for Environment and Development" (Rio de Janeiro, 3-14 June 1992) and named "Earth Summit". The output of the conference was a series of principles adopted by 178 countries and becomes the reference document for SD policies.

Such principles, (UN, Agenda 21, the United Nations Programme of Actions from Rio, 1992) broaden and complete those expressed by the Brundtland Report, highlighting the need of integration between economic development and environmental control, the need of specific regulation adapted to each countries' needs and that of a consensus and participatory approach in policy development. Furthermore, the summit guidelines are divided into four areas of interest which represents the main addressee of the development principles, and for which action plans are detailed. The four areas are: socio-economic area; resource area; stakeholder's area; implementation tools.

1.2.1.3 World Summit on Sustainable Development, Johannesburg, South Africa (2002)

Similarly to the previously described conferences, the Johannesburg declaration also included the millennium goals, developed and published by the UN in 2000. After describing the guiding principles, this meeting, ended up with a specific 'plan of implementation', addressing themes like poverty (with specific references to water and energy issues), unsustainable patterns of consumption and production, natural resources management and biodiversity conservation, health protection, with specific references to small island and developing countries, firstly affected by unsustainable changes. The plan of implementation of the Johannesburg (UN, 2002) summit highly stresses that, for implementing such goals, cooperation and partnership, both national and internationally, would require financial and macro-economic policies, public and private, with less relevant concern addressed to public health.

Interestingly, the institutional framework for sustainable development, at all levels, should provide "*Measures to strengthen institutional arrangements on sustainable development at all levels*", integrating "*economic, social and environmental dimensions of sustainable development in a balanced manner*" (UN, 2002)

1.2.1.4 UN indicators for sustainable development (2006)

Given the need of measuring SD in its quantitative and objective elements, highlighted as a fundamental principle in the previously described conferences, in 2006 the Commission for Sustainable Development developed a series of 96 indicators (UN, Indicators of Sustainable Development, 2006), divided by 50 core and 46 non-core indicators) related to 16 areas, divided in 4 categories (social, environmental, economic and institutional). The economic framework considers the economic development indicators and consumption/production patterns and accounts for a relevant quota of total indicators (33 over a total 96), while environmental indicators, are specifically referred to air, soil, fresh/marine waters and biodiversity categories accounts for 34 indicators). Social components accounts for 29 indicators, while 6 indicators are considered for global

1.2.2 Sustainable Development: European Outlook

Despite the relevance of 'sustainable growth' related to environmental issues was considered on marginal declaration at the bottom of Maastricht Treatment (1992), only the following Amsterdam Treatment (1997) declared that the European community should be "*determined to promote economic and social progress for their peoples, taking into account the principle of sustainable development and within the context of the accomplishment of the internal market and of reinforced cohesion and environmental protection, and to implement policies ensuring that advances in economic integration are accompanied by parallel progress in* other fields" (art.1). Furthermore, "*environmental protection requirements must be integrated into the definition and implementation of the Community policies and activities (…), in particular with a view to promoting sustainable development*". Firstly, the strict relationship between environmental protection and sustainable development is therefore outlined on a European level. A part from these general assertion, no specific strategies have been adopted towards sustainable development by the European Community before the Lisbon strategy (2000), the Goteborg Summit (2001), and the Brussels strategy (2005), renewed in 2009. The Lisbon Strategy tackles – without regulatory bindings – the themes of sustainable economic growth, sustainable jobs, sustainable finance, while environmental issues are only implicitly considered. Goteborg summit and Brussels strategies are specifically analyzed.

1.2.2.1 Goteborg Summit (2001)

The work of the European Commission (EU, 2001) proposed a common strategy for the European Union, being guided by the UN works of the Brundtland Commission and the Rio Conference. The report focus on defining long-term goals and defines a series of issues to be tackled such as global warming issues, threats to public health (new strains of diseases, long term exposition to hazardous chemicals, food safety), poverty, low birth rates and population ageing, loss of biodiversity, increase of waste volumes and soil loss and transport congestion. The meeting also urged the preparation, by the nations, of a specific national strategy for sustainable development, similarly to what proposed by the Agenda 21 section on national legislation.

1.2.2.2 The Brussels Strategy (2005)

With the explicit aim of re-launching the Lisbon Strategy, the EU Council tackled sustainable development as one of the four major issues, together with financial perspective, freedom/justice and external relations improvement. The commission adopted some guiding principles for sustainable development (EU, Presidency Conclusions , 2005), promoting the adoption of *"targets, indicators and an effective monitoring procedure "The* key objectives considered by the EU consider environmental protection, social equity, economic prosperity while meeting international responsibilities. Guidelines referred to the promotion and protection of fundamental rights, solidarity between generations, open/democratic society, citizen/business involvement, public coherence, governance and policy integration, use of best available technologies, precautionary and polluter principles.

1.2.2.3 Renewed EU Strategy for Sustainable Development (2009)

This work from the Commission of the European Communities (EU, Integrare lo sviluppo sostenibile nelle politiche dell'UE: riesame 2009 della strategia dell'Unione europea per lo sviluppo sostenibile, 2009) highlighted the role of sustainable development as a global objective for the EU. Given the economic downturn, the strategy also addresses the need of coupling the need to return to growth to that of sustainability. The report also refers to a European Set of Indicators for Sustainable Development, monitored by Eurostat. "Economic prosperity" represents the main objective to be achieved and for which indicators are defined, together with some other key challenges such as: climate change and energy; sustainable transport; sustainable consumption and production; conservation and management of natural resources; public health; social inclusion; demographic changes; global partnership; good governance. More than 100 indicators have been developed, with 'headline' indicators for each theme previously described.

1.2.3 National Strategies

1.2.3.1 Italian Strategy for Sustainable Development

The Italian strategy for sustainable development necessarily followed the European framework on the subject. In 2002, the CIPE (Comitato Interministeriale di Programmazione Economica), receiving the Agenda 21 principles and in preparation to the Johannesburg summit, elaborated an "Environmental Action strategy for sustainable Development in Italy" (CIPE, 2002), which considered, as objectives the following areas (and sub-areas): climate and atmosphere; nature and biodiversity; Environmental and urban quality; sustainable use of natural resources.

The correspondence between Sustainable Development and Environmental Protection is clear from the Italian National policies, which excluded some of the principles and themes described by the UN and EU guidelines (e.g. economic development), while focusing only on the environmental issues. The strategy also included indicators and target values for the identified areas.

1.2.4 Sustainable Development Policies: a critical analysis

International, European and Italian policies for Sustainable Development has been previously addressed. Some commonalities can be identified:

1. The need of indicators, target and measures for assessing sustainability;
2. The need of an interdisciplinary approach to tackle sustainability issues;
3. The need of a participatory approach.

A closer look on the so-called "three pillars of sustainability" (economic, social and environmental) shows how they are differently treated by the three references considered (figure 1.5). The Brundtland Report, and the following Rio and Johannesburg summits, is characterized by a balanced contribution of the three aspects, while the need of their integration is often emphasized. The European outlook, from the Amsterdam Treaty (1997), while stressing the multi-lateral approach to sustainable development, also says that "*environmental protection requirements must be integrated into the definition and implementation of the Community policies* *and activities (…), in particular with a view to promoting sustainable development*". In 2009, however, the renewed strategy for sustainable development put "economic prosperity" as the first and most relevant objective of the strategy. The Italian strategy (2002), as previously described, only considered the environmental aspects of sustainable development.

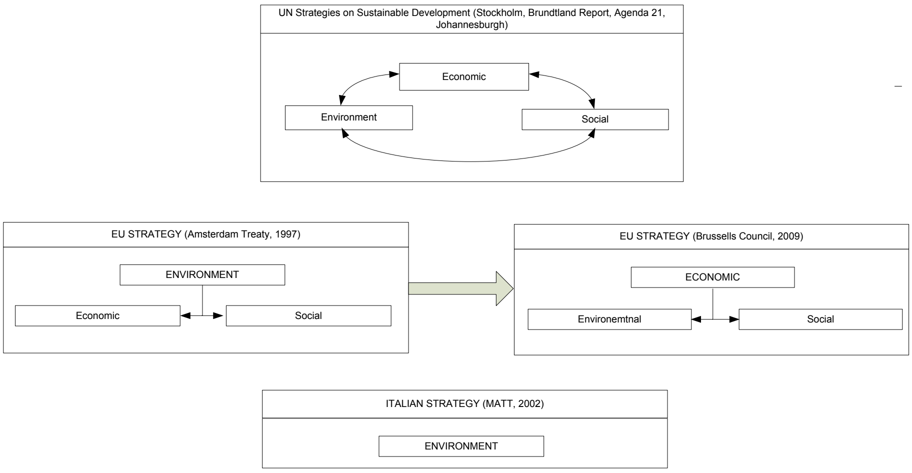

Figure 1.5: Benchmarking UN, EU and Italian SD strategies

1.2.5 Sustainable Development and role of industry

As previously outlined, the need of an interdisciplinary approach when tackling sustainable development issues, has led to a major contribution attributed to the industrial and manufacturing industry. The Brundtland Report, for example, considers the manufacturing industry as one of the main addressee to the policies, and as one of the main actors on SD. The report also highlights the need of reducing the resource usage, while contemporary increasing production due to the contingent demand increase guided by the demographic trend. The report highlights the on-going reduction in resource intensity and the relevance of a Life-Cycle Approach to the industrial sector, as it will be later discussed. On the report, furthermore, the relevance of Polluter Pays Principle (PPP) is highlighted, as it's pointed out that the effectiveness in terms of impact reduction (but also expenditure reduction) of environmental solutions to the productive processes.

From the strategic viewpoint, the report highlights the relevance of defining environmental objectives in manufacturing, realizing regulations, standards and benefits systems. Particular emphasis is given to the use of economic tools for such goal. The need of encouraging broad environmental impact assessments, especially in Small and Medium Enterprises (SME) is also another direction proposed the report, as the identification of industrial risks (particularly focusing on chemical products, hazardous wastes and industrial safety) and the improve of international cooperation for developing countries.

The Rio conference (1992), acknowledged the role of industry in the SD policies. Sustainable development of more efficient production processes in emphasized, as the use of pre-emptive strategies for reducing impacts, development and technology innovation in the field of "Cleaner Production", while considering a Life-Cycle Approach. The relevance of Environmental Management is also highlighted as a key to SD.

At a European Level, the Lisbon Council (2000) refers to the "*companies' corporate sense of social responsibility regarding best practices on lifelong learning, work organization, equal opportunities, social inclusion and sustainable development*", without providing specific operational support. Similarly, Bruxelles council (2009) points out that the social responsibility of companies would allow to conciliate economic, social and environmental goals, together improving the capacity of the EU in terms of sustainable development.

On a national level, considering Italian strategy on SD, the role of manufacturing industry is directly addressed by identifying indicators and reduction targets together with specific actions to be adopts such as reducing energy consumption and energy/emissions intensities, minimizing resource use, adopting international standards on pollutants emissions, water reuse and water reclamation, disposed waste reduction, and material recovery.

The interest towards sustainable development has experienced a rapid growth in recent years. A simple search on Scopus (ScienceDirect, 2011) of the exact words "Sustainable Development" shows that the number of publications on this subject has growth exponentially over the last three decades (Figure 1.6).

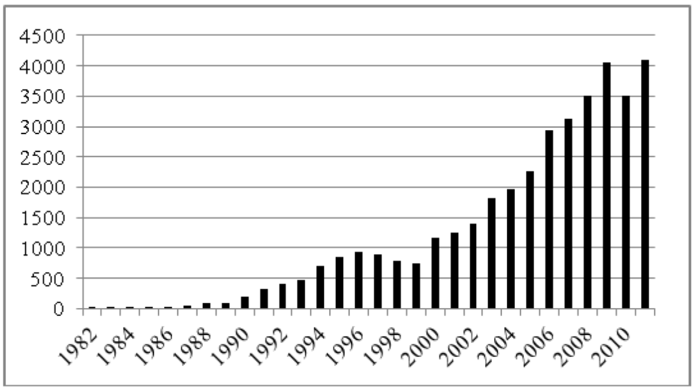

Figure 1.6: Academic literature on Sustainable Development: evolution from 1982 to 2011

1.3 Industrial Ecology

The relevance of the manufacturing industry in the SD process has been highlighted in the previous paragraphs. Furthermore, the emphasis on the "environmental pillar" of sustainability has been pointed out, mostly relating to the Italian case. The union between the need of industrial development and increased attention to environmental sustainability has led to the development of a new scientific discipline which would consider such aspects in a holistic way, under the name of *"Industrial Ecology"*. Given this very peculiar formation process, Industrial Ecology (IE) mutates and applies concepts from multiple disciplines, and its multi-disciplinary approach represents its peculiar feature.

Starting from the seminal work for Industrial Ecology, attributed to (Gallopolous, 1989) and published on the journal "Scientific American", many expressions have been used for expressing the concept of IE, all of them with similar meaning: industrial symbiosis, cleaner production, eco-industrial parks are just some of them, reflecting slight variations on the main concept of Industrial Ecology. White (1994) defined Industrial Ecology as '*the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and* *of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources'.* As pointed out by (Ayres, 1994) the double focus of this discipline in both industrial, because it refers to the manufacturing and production of goods in all its stages ('from cradle to grave'), while is 'ecological' because of the natural analogy with biological systems, which are taken as a reference for the capacity of reducing inputs material and re-using waste outputs, in opposition to the traditional industrial system, which operates on a linear model.

Industrial ecology provides the basis for analyzing and improving current production processes and aims to improve environmental quality while simultaneously providing the economic needs of the company in situations of mutual benefit (Roberts, 2004). Some of the principles of industrial ecology are reported by (Roberts, 2004) as:

- Promoting opportunities for creating alliances and efforts from communities and policy-makers to develop an active behavior for sustainable practices in industry;
- Strategically co-locating companies to optimize by-products collection and re-use;
- Creating value-added opportunities by means of applying practices of energy and waste recovery in industrial systems;
- Catalyzing synergies among companies and provide a favorable environmental for cleaner technologies development;
- Providing infrastructure for promoting industrial development of companies supporting SD practices, while maintaining high level of innovation and competitiveness;
- Supporting industrial policies and incentives for promoting innovation, collaboration and commercialization of new, low-impacting products;

The multi-disciplinary approach offered by the discipline led to the formation of various approaches towards industrial ecology, often borrowed from other disciplines. The main variables (Van Berkel, 2010) for the different industrial ecology approach are:

- Temporal approach: reactive or preventive
- Motivation: corporate responsibility, business opportunity, environmental legislation;
- Focus: single pollutant, process/facility, lifecycle/system
- Discharge route: single or multi compartment.

Such distinction led to various approaches, broadly ascribable to industrial ecology, such as

- Design for Environment: refers to the managerial approach, anticipating product or process commercialization, involving the planning ahead considering the potential environmental impact from both quantitative and qualitative aspects, the latter referring to reducing toxics use in products:
- Eco-Efficiency: refers to the efficient use of non-renewable resources, mainly energy and raw materials on a quantitative level, generally reducing the use of resources for products while guarantying the same functionalities, thus increasing the value of the product in an economic-sound way;
- Waste Minimization: preventive approach to waste issues, it aims to reduce the amount of waste produced while increasing the quota of material recovered and/or recycled.
- Pollution Prevention and Toxic Use Reduction: preventive approach limited to pollutants impacts and toxic material use, driven by environmental constraints and economic gains;

- Cleaner Technology/Production: it refers to the use of BATs for reducing companies' environmental impact and it specifically address plant and process solutions.

While differing for specific application, those instruments shares some common principles and tools which find their theoretical base on the "System Approach" theory, and will be analyzed over the following paragraphs.

1.3.1 The System Approach

Systemic approach, or System Analysis, represents a mathematical modellization of a system, featuring relations, constraints and objectives among the various components of the system itself. (Ayres, 1994). Such model is in general the results of a preliminary assessment in which the quantitative relations among the system's components are established. The boundaries of the system might be chosen a strict level (e.g. a single plant) or on a broader level (e.g. including suppliers/clients, etc.). The focus of Systems Analysis (Ayres, 1994) is an objective function, presenting a uniform unit of measurement (e.g. dollars/Euros). Seager et al (2001), found in (Ayres, 1994), acknowledge that System Analysis is a design tool assisting decisor maker to concentrates all the components of a system towards a single objective. While most of the authors focus on economic objectives, Horvath et al (1995), believe that not all the commercial operation are guided by profit maximization.

Four elements define the Systems Approach, as outlined by (Mingers & White, 2007), that is:

- The holistic approach, i.e. the concept of considering a system as and interrelated group of entities interacting among each other, instead of separated ones;
- The relevance of the relationship among such entities, with those links even more important than the elements themselves;
- The view of a system as a hierarchy of levels and sub-systems, with variable properties emerging at different levels of the hierarchy itself;
- Especially for social systems, the notion that people will act following their various sensibilities, purposes and rationalities;

1.3.2 Tools for industrial ecology

An important feature of system analysis and, on a broader level, Industrial Ecology, is its black box approach, in which material, energy, products and by-products flows are assessed regardless of the core process involving the exploitation or production, but only on an input/output basis. Such approach, while limited in its deepness, allows keeping a broad eye on the whole system itself, linking processes a production the upper level of plant management.

All this considered, the following tools are reported by (Ayres, 1994) as the major tool for assisting industrial ecology in a system analysis approach:

- Substance Flow Analysis (SFA);
- Material Flow Analysis (MFA);
- Life cycle Assessment (LCA);

Those tools, associated respectively for chemicals, materials or products assessment, allows to monitor and control companies' impacts by focusing on impacts per unit flow (type I methodologies), while, on a broader level, the so-called type II methodologies are used for company, sectorial or regional assessment, and are defined as Process Analysis (PA), Industry Analysis and Economy-Wide MFA, or regional total material requirement (TMR)

A comparison among them has been provided on Table 1.2.

Table 1.2: Industrial Ecology Tools benchmark. Elaborated from (Ayres, 1994)

	SFA	MFA – EWMFA	LCA	PA
Subject	Single Chemicals	Materials	Products	Processes
Objective	Detoxification	Dematerialization	Impact Assessment	Optimization
Stages	Goal and Scope Inventory Evaluation	Goal and Scope Inventory Evaluation	Goal and Scope Inventory Impact Assessment Evaluation	Flow sheet Modellization Simulation Optimization
Used by	Regional or site-specific assessments	Large companies or institution	Companies	Companies
Main goal	Quantifying toxic use and evaluate substitution or toxic losses	Evaluate and improve resource efficiency by reducing total material consumption	Evaluate most relevant components or production processes for re-design and benchmark	Simulate process flow and optimize it by parameters adjusting or adding/removing components
Main advantages	Easiness to use, significance of results.	Easiness to use, benchmark indicators, indirect accounting may be used	Prioritize alternatives and internal benchmark. Impact assessment vs. quantity assessment	Optimizing company's processes, internal and external benchmark company's performances
Disadvantages	Inability to account for all output substances without direct measurement. Quantity assessment vs. impact assessment	Quantitative assessment vs. impact assessment	Using external database may not be relevant for external benchmark	Modeling and simulating need specific capabilities

1.4 Decision Support Systems and Multi-Criteria Decision Making

A Decision Support System (DSS) is defined as software-based tool assisting the decision making process by means of interacting with both internal/external user and databases, while implementing standardized or specific algorithms for problem solving (Burstein & Holsapple, 2008) DSSs belong to the broader category of Knowledge Management, where the knowledge process follow, depending on the value given to the whole process, a set of six "knowledge stages" as those represented on Figure 1.7.

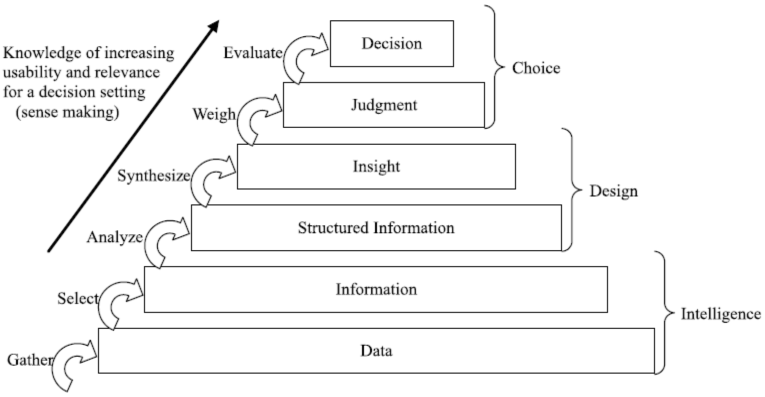

Figure 1.7: Knowledge stages (Burstein & Holsapple, 2008)

The decision making process follows an "horizontal path" (Figure 1.8), as described by the Simon model (1960), reported in (Burstein & Holsapple, 2008), from the first stages of problem classification and definition , called the "intelligence phase", the "design phase" of alternatives generation and evaluation, ended by the alternative negotiation, selection and action determination, called the "choice phase". The author underlined the relationships and interdependences between such stages, making the whole decision-making process a cyclical approach.

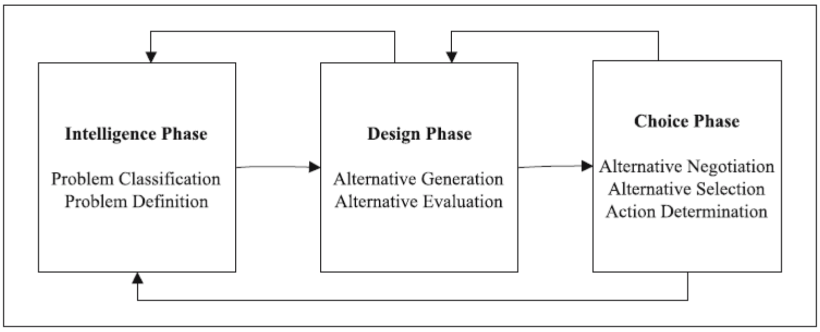

Figure 1.8: Decision Making Process (Burstein & Holsapple, 2008)

(Power, 2008) identified 4 main types of DSSs, depending on the main drivers guiding the decisional process, that is:

- Model-driven DSSs: such DSSs require limited amount of data because of the intrinsic composition of the system, used to evaluate quantitative data in a tailor-made structure suited to adapt to other external requirements. Firstly developed for financial planning, such category of DSS were later used for multi-criteria decision making and spatial-driven decisions such as logistics or distribution modeling;

- Data-Driven DSSs: the database structure behind the DSS is emphasized and the operations of data-warehousing and manipulation are the most relevant for such DSSs. Online – in the meaning of interactive (such as the OLAP) and offline – application can be found, while web-based data-driven DSSs currently represent the natural evolutions of such models;
- Communication-Driven DSSs, are used for exploiting the network and communicating capabilities of the system, which includes the use of groupware, conferencing or other computer-based newsletter. Such category is directly related to the Group DSSs, developed in order to promote participatory approach to the decision process, and their relation with model-driven DSSs have been studied, aiming to include the shared approach of the former, with the structured modeling of the latter.
- Document-driven DSSs, also called "text-oriented DSS", they are used for document retrieval, especially in large group/organization, in order to support the decision making process. Web-based system increased the possibility of such DSSs, allowing to rapidly access documents distributed in worldwide databases;
- Knowledge-driven DSSs: these are specific, tailor-made, systems used in particular domain and developed for a particular person or group of people. The author also acknowledges the relationship with Artificial Intelligence systems, in which the DSS follows a series of rules in order to evaluate and eventually take decisions on the problem to be analyzed.

Eventually, (Arnott & Pervan, 2005) reported a framework for DSS classification and sub-classification, identifying Personal Decision Support Systems, Group Support Systems, Executive Information Systems, Intelligent Decision Support Systems and Knowledge-Management-based DSS. Each of such DSSs presents sub-branches depending on their specific features and temporal evolution. Particularly, Model-Driven DSS represents the focus of this study. Modellization stage, focusing on Multi-Criteria modeling, will be investigated in the following paragraphs.

1.4.1 Multi-Criteria Decision Making

A preliminary distinction between Multi-Objective and Multi-Attribute Decision Making has to be provided. While, on general terms, DSSs requires a range a functionalities for assisting the decision making process, Multi-Criteria Decision Making "*deals with a general class of problems that involve multiple attribute, objective and goals*" (Zeleny, 1982). (Olson, 2008), retrieved in (Burstein & Holsapple, 2008) underlined the complementarities of MCDM and DSSs, especially model-driven DSSs, given their different approach in terms of "*philosophies, objectives, support mechanisms and relative support roles*". Multi-criteria, multi-attribute and multi-objective decision making, while similar in their main concepts of integrating, optimizing and finalizing the decision making process, present some major differences which will be now assessed.

While similar in their final purpose – assisting decision making process – Multi-Criteria, Multi-Attribute and Multi-Objective analysis differs strongly because of their basilar concepts beneath. As reported by (Pohekar & Ramachandran, 2004), while Multi-Criteria Decision Making represent the major class of Model-Driven Decision Making Support System, Multi-Attribute and Multi-Objective represent its subclass (fig.1.9), relating to more specific approaches to the decision model.

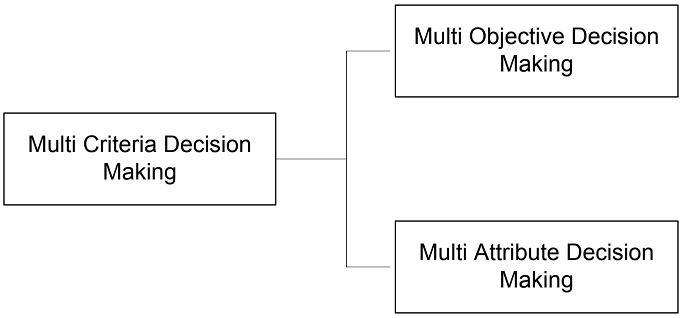

Figure 1.9: Multi-Criteria Decision Making. Elaborated from (Pohekar & Ramachandran, 2004)

1.4.2 Multi-Objective Analysis

The identification of the best solution – or set of solutions – for a specific problem has been traditionally considered in decision making problems. (Weise, 2009) have classified optimization techniques according to their method of operation (deterministic and probabilistic algorithms), and to their properties (optimization speed, number of objectives). Deterministic algorithms are used when *"a clear distinction between the characteristics of the possible solutions and their utility for a given problem exists"* (Weise, 2009). Probabilistic algorithms are used when "the relation between a solution candidate and its fitness are not obvious or too complicated". A typical deterministic algorithms is the "branch and bound", while Monte Carlo techniques are considered the pioneer in probabilistic algorithms. Other criteria for algorithms classification are optimization speed and objective number. Regarding the former, in *offline optimization* time does not represent a constraint, while optimization can take long time to be executed and get to the optimal result; in online optimization continuous optimization is required instead, thus needing for rapid algorithms, even at the expense of the accuracy of the solution required. Considering the number of objectives, single-objective and multi-objective algorithms can be identified. Given the multidisciplinary approach, described previously in this chapter, required when referring to the industrial ecology issues, multi-objective methodologies will now be assessed in details.

1.4.2.1 Multi-objective Optimization Techniques

Optimization with multiple objectives conflicting with each other has no single best solution (like most of the single-objective functions), but a set of solutions, named the "Pareto-set", from the name of Villfred Pareto (1848-1923), which firstly studied them, applying to social science, economy and game theory. Multi-objectives optimization techniques therefore identify a set of non-dominated solutions which represent the *optimums* for a given problem. The concept of domination can be translated by the expression that: an alternative *a* is non-dominated by *b* if *a* is better than *b* for at least one objective, while not being worse than b for all of them. Graphically, the concept of domination can be viewed in the minimization problem of figure 1.10, taken from (Alarcon-Rodriguez, Ault, & Galloway, 2010). Given a range of feasible solutions (the small squares in the graphs) the Pareto front is defined as the set of solutions which cannot be improved in one of the objective (f1 or f2) without worsening the performance of the second.

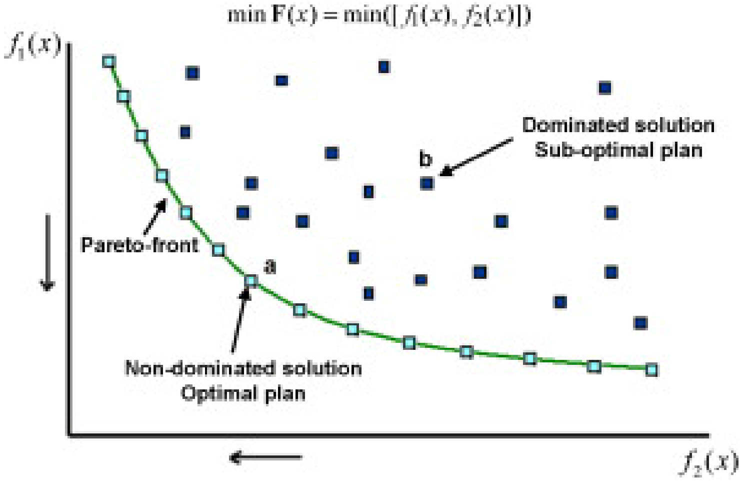

Figure 1.10: Pareto front for Multi-Objective Optimization, from (Alarcon-Rodriguez, Ault, & Galloway, 2010)

Identifying the Pareto front means also satisfying the following requisites for the solutions identified, as reported (Alarcon-Rodriguez, Ault, & Galloway, 2010).

- Spread: To find a set of solutions that "capture the whole spectrum" of the true Pareto front.
- Accuracy: To find a set of solutions as close to the real Pareto front as possible;
- Diversity: To find a set of solutions as diverse as possible;

Among the multi-objective optimization techniques, a particular choice has been made, selecting evolutionary algorithms for the objective of this work. The main reason for selecting such methods has been the particular "black-box" approach, as reported by (Weise, 2009) of those methods, which make them suitable for a variety of problems as those referred to the main theme of this work, that is the sustainability of the industrial sector.

1.4.2.1.1Evolutionary Algorithms

Evolutionary algorithms are defined as "*population based metaheuristic optimization algorithms that use biology-inspired mechanisms like mutation, crossover, natural selection and survival of the fittest in order to refine a set of solution candidates iteratively*" (Weise, 2009) Firstly, the concept of metaheuristic is defined as a "method for solving general problems, combining objective functions in an abstract way, treating problems as a black box" (Weise, 2009) The five main stages of an evolutionary algorithms involves

1. Initial population, which allows to create the initial sample to be analyzed from the possible set of candidate solutions;
2. Evaluation, which computes the objective value from the candidate solution;
3. Fitness Assignment, which, depending on the objectives value, determines the fitness of the candidate solution relatively to a fitness criteria (weighed sum of objectives values, Pareto ranking, etc.) which evaluates the suitability of the candidates to the optimization required;
4. Selection: basing on the fitness of the candidate solution, at this stage the population (the group of candidate solutions) to be maintained is selected, while the rest is discarded.
5. Reproduction: selected candidate solutions are reproduced by different mechanisms such as partial mutation, crossovers, or complete change.

The family of Evolutionary Algorithms (Weise, 2009) includes:

- Evolution Strategies
- Genetic Algorithms
- Genetic Programming
- Learning Classifier Systems

Most relevant features of the methodologies for Multi-Objective decision making are summarized on table 1.3.

Table 1.3: Multi-Objective Decision Making: a synthesis of the methodologies. Elaborated from (Weise, 2009)

	Evolutionary Strategies	**Genetic Algorithms**	**Genetic Programming**	**Learning Classifying Strategies**
Objective	Multi-objective evaluation of candidates solutions	Multi-objective evaluation of candidates solutions	Process identification from initially known inputs and outputs	Adapting decision process to the environment input and deciding output actions
Population Type	Vector of real numbers, eventually extracted from statistical distribution	Fixed- or variable-length binary strings	Decision Tree with operators as nodes and data/variables as leaves.	Binary strings computed from external detectors
Evaluation	Comparison to objective function	Mapping to phenotype, the latter compared to objective function	Comparing initial i/o with achieved i/o	Mapping input strings with a set of rules (if-then) and updating strings with action to be taken
Fitness assignment and selection, reproduction	Hill climbing (one to one selection) parent deletion or of parent+offspring selection (Mutation)	Creation, Mutation, Crossover, Permutation	Creation, Mutation, Crossover, Permutation, Recombination, Encapsulation, Wrapping and Lifting	Rules update basing on environment input and nested genetic algorithms for rules updating

1.4.3 Multi-Attribute Decision Making

Under the common name of Multi-Criteria Decision Making, Pohekar and Ramachanfran (2004) have reviewed the most used methodologies used in sustainable energy planning. Despite the specific topic treated by the authors, this work provides a useful framework comparing the different methodologies which, given the considerations provided in the previous section, are considered as Multi-Attribute processes given that they deal with an established set of alternatives. The authors identified the following methodologies:

- Weighed Sum Method (WSM);
- Weighed Product Method (WPM);
- Analytical Hierarchy Process (AHP)
- Preference Ranking Organization Method For Enrichment Evaluation (PROMETHEE);
- Elimination And Choice Translating Reality (ELECTRE);
- Compromise Programming (CP);
- Multi-Attribute Utility Theory (MAUT)

A more general taxonomy of MADM has been given by (Stewart & Belton, 2002), considering the following types of methodology

- Value measuring methodologies: this category considers methodologies which associates a numerical value to each of the alternatives to be assessed, for each criteria considered. These are the most common models for alternatives' selection;
- Outranking models: In this category the so-called "French school" of outranking MCDM methodologies is described. An outranking relation, as firstly described by Roy and reviewed by (Behzadian, Kazemzadeh, & M., 2010), is a "*binary relation S defined on the set of alternatives A, such that for any pair of alternative* (A_i, A_k) Є *A x A:* A_iSA_k *if, given what is known about the preferences of the decision maker, the quality of the evaluations of the alternatives and the nature of the problem under consideration, there are sufficient arguments to state the alternative* A_i *is at least as good as* A_k*, while at the same time no strong reason exists to refuse this statement*". Such definition encompass many different features as the presence of preference ("there are sufficient arguments"), or indifference functions ("no strong reason exists"),
- Reference, goal and aspiration models: In this category falls a range of methodologies border line with multi-objective decision making, classified in Goal Programming, Step Methods (STEM) and TOPSIS methodologies. Such type of methodologies, while keeping dealing with a fixed range of pre-decided alternatives, aim to optimize the decision making process keeping one or more objectives to be maximized or minimized.

Table 1.4 summarizes the most relevant methods for each category.

Table 1.4: Multi-Attribute Decision Making: a synthesis of the methodologies

	Value measuring	**Outranking models**	**Reference, goal and aspiration**
Basic Principles	Association of a numerical value to each of the alternatives to be assessed, for each criteria considered	Evaluating alternatives depending on preference or indifference functions.	Optimize the decision making process keeping one or more objectives to be maximized or minimized
Examples	1) Weighed Sum/Products 2) AHP 3) Compromise Programming	1) ELECTRE 2) PROMETHEE	1) Goal Programming 2) STEP Methods 3) TOPSIS
Advantages	Simplicityand broad use (1); Adherence to the DM process by pair wise comparison, 2,3,	Adherence to the DM process by pair wise comparison, preference/ indifference and veto thresholds:	Interaction with the decisor maker (objectives' relaxing or tightening, 2) Adherence to the DM process
Disadvantages	Uniformity of unit of measurements Consistency of judgments (1, 2); Optimal solution to be known (3); Subjectivity of weights	Indifference, veto and preference threshold to be determined; Complexity of the exploitation procedure (2)	Ideal/Anti-Ideal solutions to be known (2,3); Weight definition (1)

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2

Research Background

Sustainable Development policy is based on the “three pillars”, previously described, of economic, environmental and social sustainability. Keeping this in mind, the research background, considering the scope on energy systems provided in the introductive chapter will be assessed. Particularly, the focus will be on energy producing technologies to be used in innovative installations on stationary industrial systems, with a particular focus on Combining Heating and Power Technologies (CHP) from both fossil and renewable sources, assessing:

- Technological and economic aspects;
- Environmental aspects;
- Normative aspects;

Most relevant technologies for industrial use will be assessed from the technical, economic and environmental viewpoint. Environmental impact assessment will be taken into consideration assessing the various methodologies used for accounting the impact of different toxicants on a local and global scale. Eventually, regulation affecting both technology choice and environmental control will be evaluated, with specific reference to the Italian scenario. A comprehensive background of the possible technologies for energy production is provided on Figure 2.1. Such model, called Reference Energy System (RES) distinguishes between Primary Sources (Fossil, Solar, Biomass, etc.), Energy Converting technologies (Boilers, Engines, ecc), Type of Energy produced (heat, power, cold), final distribution system.

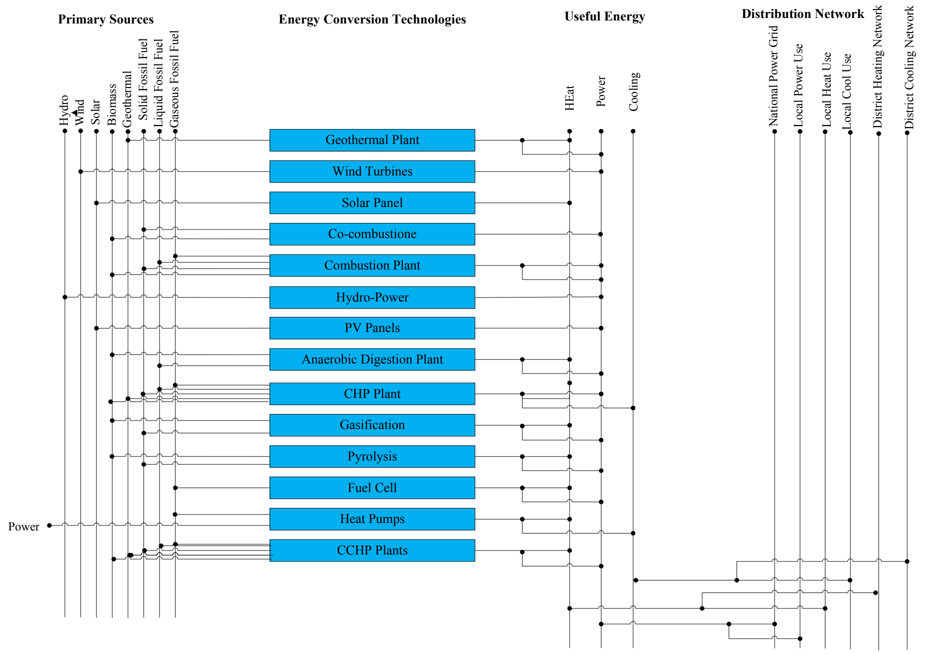


Figure 2.1: RES scheme

While referring to most of the technologies being shown on figure 2.1, this work will focus particularly on CHP plants and PV panels, providing detailed background information which will be used later on for the modeling process.

2.1 Techno-Economic Background

Combined Heating and Power (CHP) Plants represent an effective way to both produce power, while recovering heat (hot water or air) to be used inside the company's premises. This technology might be coupled with cooling equipment (absorption machines) for combined cooling and heating plants. CHP installations broadly diffused worldwide which will be detailed are:

- Reciprocating Engines
  - Gas fired;
  - Diesel fired;
  - Bio-oil fired
- Gas turbines
  - Variable-speed micro-turbines;
  - Fixed-speed medium sized turbines
- Fuel Cells

For each of such technologies, technical (operating principles, design features, efficiencies, fuel to be used) economic (capital, operating and maintenance costs) and environmental (specific emission rates) aspects will be assessed. Furthermore, PV plants will also be taken into consideration because of their flexibility to be used in both civil and industrial environments. Electrical efficiency, from now on, will be referred to the lower heating valued of the fuel, while heat recovery efficiencies is assumed for hot water production at medium temperature 60/80 °C, as reported from most of the manufacturers.

Fuel consumption are generally provided by manufacturers in terms of fuel combustion per hour. Given the direct relationship with power efficiency, power input and lower calorific value,all the specific fuel consumption have been derived from manufacturer data reported in (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009), adapted to the objective of this assessment.

2.1.1 Reciprocating Internal Combustion Engines

Internal combustion engines are derived from naval and automotive application of traditional 4-strokes or 2-strokes mobile engines. The basic principles for ICEs energy production is crank-shaft maneuvering deriving from air-fuel combustion. Crankshaft movement is linked to a piston sequentially coupled to gearings/shaft and alternator for power production. The inlet air is pressurized by compressor coupled to the turbo-expander for exhaust gas cooling and expansion. Compressed inlet air is then cooled for increasing energy conversion efficiency by means of an intercooler. Number of cylinders, depending on plant size, might vary from 12 to 16.

Hot water (90-120°C) can be produced from the heat recovery of ICE's system and can be used for space heating or for process use. Steam can also be produced, but only on large scale application and with no stringent conditions of pressure and temperature required.

2.1.1.1 Technical features

Large use and diffusion of ICEs, together with their capability of performing well at partial load (down to 30%). The choice of the different modes of operations strictly depends on plant-specific conditions (cooling towers already present, heat/power buying cost and selling price) and machine (part-load efficiencies). Topping cycles – where power is produced and heat is recovered from resulting energy – are used in CHP applications, whereas bottoming cycles – power produced from exhausted after-use heat – are present only when high-quality and quantity heat – usually steam - is required for process uses. Other issues such as fuel, sizes, efficiencies and maintenance needs are discussed over the next paragraphs.

2.1.1.1.1Fuel used

Natural Gas and Diesel are the most common fuels for ICEs. Fuel-oil or bio-oil, bio-gas and LPGs (Propane and Butane) or gasoline might also substitute such fuels, by modifying combustion parameters and/or pre-filtering gases, as in the case of biogas utilization.

2.1.1.1.2Available sizes

Given the broad diffusion of ICEs on a range of applications, many ICEs constructors and plant sizes are available - from 1 kW_e up to 10 MW_e) depending on parameters such as company's required heat and power loads and fuel availability. Lower sizes are justifiable only with heat recovery, and have been increasingly studied for domestic application, while small and medium size plants are used in industrial application with combined heat and power load requirements. An overview of main constructors, models and main technical features, has been derived and updated from (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009) and has been used for modeling step.

2.1.1.1.3Efficiencies

Considering full load first-principle efficiency, ICEs electrical output varies from 25% to 47% of total input depending on plant size. Extrapolating data from (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009), there's a statistically significant trend of electrical efficiency versus rated power output (Figure 2.2). Efficiency is calculated with respect to the Lower Heating Value, therefore what fuel to be used is not considered at this stage. Efficiencies diminishes at partial load (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009) and (US-EPA, Technology Characterization: Reciprocating Engines, 2008), from, losing averagely absolute 5-6% (relatively 16%) from full to 30% of the load: such performance, especially when compared to other power production technologies, is considered quite good, allowing to use ICEs as modulating/peak power systems. Thermal efficiency shows an opposite trend compared to power performance – logically the more specific power produced, the less heat recovered – with less statistical evidence (R^2) on the fittest distribution rating thermal efficiency and power output.

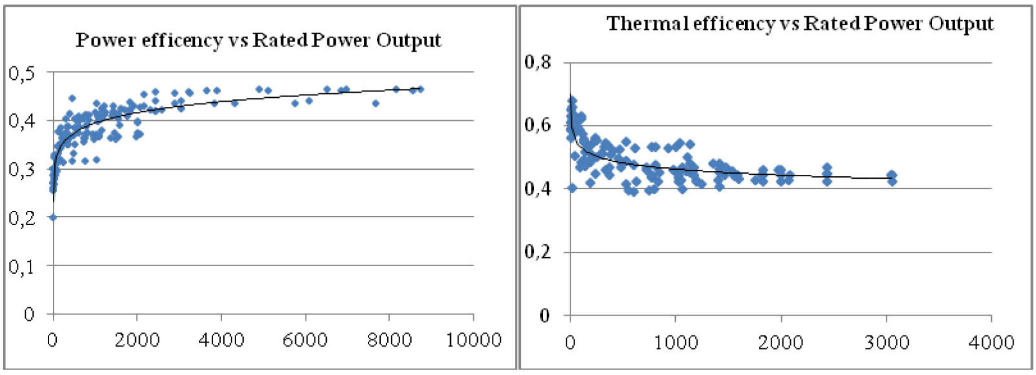


Figure 2.2: Power efficiencies (a) and thermal efficiency (b) vs rated output

2.1.1.1.4Maintenance

Given the large number of moving parts, maintenance represents a major aspect for ICEs. Regular maintenance has to be provided for bearings, filters, oil, lubricant and spark plugs. After a number of operating hours, minor overhaul involving cylinders head and turbo-expander has to be performed, while extraordinary maintenance is required for substituting cylinder heads and piston/liner replacement. The time between successive maintenance depends on engine speed, as reported in (US-EPA, 2008). Despite the intensive maintenance required for CHP systems, such equipment presents a high efficiency in terms of plant availability. Considering a base-load 24/7 operations, ICE's availability has been computed by (US-EPA, 2008) as 94.5 % for 80-800 kWe Gas Engines and 91.2% for rated powers superior to 800 kWe systems.

2.1.1.2 Economic considerations

The traditional distinction between fixed and variable costs can be considered for ICE's costing. Two major considerations impact on ICE's fixed costs:

- ICE's investment;
- ICE's regular maintenance

Variable costs depends on fuel use and variable maintenance, depending on heat and power outputs, which in turns depend on operating conditions (working hours, heat and power loads, etc.). Total investment, maintenance, and operating costs will be considered in the following paragraphs.

2.1.1.2.1Capital costs

Capital costs of ICE strictly depend on site specific features and local distributors availability. Considering this relevant premise, an order of magnitude can be provided depending on plant size. (US-EPA, 2008), identified the following main items in ICE's costing.

- Total equipment costs (generation set package, heat recovery system, interconnections and electrical wires), 59% of capital costs;
- Labor and materials (L&M), 18%;
- Project management, construction and engineering fees and contingencies, 23%.

Specific cost trends depending on plant power output, taken from (US-EPA, 2008), are reported on Figure 2.3 considering natural gas fuelled-ICEs.

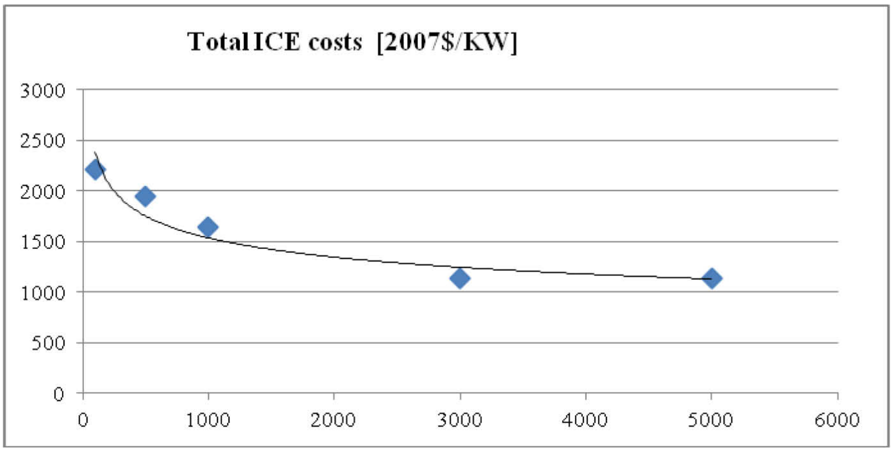


Figure 2.3: ICE capital costs depending on plant size

A similar trend in ICE capital costs is provided by (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009), reporting 700-1000€/kW for 100kW – 10MW plants, 1500-2500 €/kW for 5-100 kW installations.

2.1.1.2.2Maintenance costs

Given the previously described need for maintenance in ICE, such cost represents a relevant factor when calculating total plant costs. Fixed and variable maintenance costs have been provided by (US-EPA, 2008), depending on plant size, expressed in 2007$. Maintenance costs varies from 0.9 to 2.2 c$/kWh, with higher values have been reported from (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009), ranging from 0.8 c€/kWh to 2.5 c€/kWh.

2.1.1.3 Environmental considerations

Emissions from ICEs are mainly due to fuel type chosen, operating conditions and abatement technologies. The main fuel used in ICEs, natural gas, is no-sulfur fuel with negligible amount of particulate matter. Therefore, main pollutants to be considered are NO_x which, given the low amount of fuel-bound nitrogen, depends in turns on rich-burn or lean burn conditions and on the presence of abatement technologies – and carbon monoxide (CO), which is the result of partial carbon oxidation (incomplete combustion), strictly depending on operating conditions.

For reducing NO_x emissions of ICEs, and referring to operative modifications of combustion processes, the following operations are identified by (EPA-California, 1997) for compression-ignited engines, such as injection time retarding; modified injectors; turbo-charging and intercooling of injected air; recirculation of exhausted; pre-combustion chambers works as a two-stage combustion where injection is retarded and different fuel-air mixed can be used; water injection and thermal barriers coatings may also be used for NOx reduction. Spark-ignition engines, present NOx reduction techniques as pre-stratified charge, air to fuel ratio adjusting, clean burn engines or pre-combustion chambers.

The analysis of NO_x and CO emissions from ICEs, extrapolated from commercially available data from producers, shows that there's no specific trend in NO_x emissions. Reported emissions are mainly based on regulatory limits rather than actual emission levels. Different operating conditions of each motor (mainly excess air and temperatures) and the abatement technologies installed on each engine, not readily available from producer's catalogue are also a source of uncertainty.

Keeping in mind this relevant consideration, a two-step trend, however, can be extrapolated, showing two limits in NO_x emissions fixed at 250 and 500 mg/Nm3. Similarly CO emissions depends on combustion efficiency of ICE, mainly due to excess air presence which lead to more complete combustions and lower CO concentrations on exhaust gases. However, rated CO output from ICE are generally limited to 300 mg/Nm3, mainly because plant producers tend to limit incomplete combustion which would lead to process inefficiency.

Emission rates described from IPCC database (IPCC, 2011) does not take into account cogenerating engines, while similar standards from the USEPA, the AP 42 (US-EPA, Emissions Factors & AP 42, Compilation of Air Pollutant Emission Factors, 2011) provide values for stationary combustion sources. CHP emission factors have been reported, depending on the type of fuel used, on table 2.1, providing both the unit of measurement used by US standards (lb/MMbtu) converted to most commonly EU used standards (g/MJ). Unit of measurements of such emission factors are expressed in terms of mass per input energy. The table refers to both NO_x and CO emissions, but also including PM10, Non Methane Volatile Organic compounds, and SO_x.

Table 2.1: Emission factors of Internal Combustion Engines (from US, AP42 Standards)

	NOx		CO	
	lb/MMBtu	g/MJ	lb/MMBtu	g/MJ
Natural Gas 4-strokes ICEs	2.2100	0.9502	3.7200	1.5994
Diesel ICEs	4.4100	1.8961	0.9500	0.4085
	NMVOC		PM 10	
	lb/MMBtu	g/MJ	lb/MMBtu	g/MJ
Natural Gas 4-strokes ICEs	0.0296	0.0127	0.0095	0.0041
Diesel ICEs	0.3185	0.1369	0.3100	0.1333
	SO2			
	lb/MMBtu	g/MJ		
Natural Gas 4-strokes ICEs	0.0006	0.0003		
Diesel ICEs	0.2900	0.1247		

Canova et al. [2008] also reported emission trend for small scale ICE depending on power output for NOx, CO and non-methane organic compounds (NMOC). Biodiesel/bio-oil emissions factors from stationary ICE have been not been found in either US or EU standards. Therefore mobile sources have been taken as a reference. The 2002 US-EPA report on biodiesel substitution shows a reduced trend in PM, CO (-47% at 100% substitution rate) and HC emissions (-68 %(, while an increased emission of NOx has also been reported (+10%).

2.1.2 Gas turbines

Aero-space derived gas turbines are increasingly used for small, medium and large sized solutions ($1kW_e$ – $10\ MW_e$), both for power production (in combined plants with steam recovery systems) or industrial uses, due to their benefits in terms of lower maintenance and commercial development. Micro-turbines (30 – 250 KWe) have recently found a relevant use, from domestic to small industrial applications. After assessing the main operating principles of gas turbines, design consideration featuring technical, economic and environmental issues will be assessed.

Single shaft solutions are used, with compressor, expansion and power turbines, and a generator coupled to the same single shaft. Shaft rotating speed is generally fixed for larger turbines (> 1 MW_e) for base load application, and the rotating speed is limited to power frequency needed. Micro-turbines have higher rotational speed (100.000 rpm) thus requiring current frequency adjusting, done by electronic control devices, thus increasing investment and maintenance costs.

2.1.2.1 Technical considerations

Installing a gas turbine requires the assessment of at least 4 main parameters, such as:

- Commercially available sizes;
- Fuel;
- Process efficiencies;
- Maintenance needed;

Similarly to internal combustion engine, topping, heat/power following and base load operations are available for gas turbines.

2.1.2.1.1Commercially available sizes

A broad range of small and medium size turbines are produced worldwide, ranging from $30KW_e$ Capstone to large industrial application up to 10 MW_e. A list of commercially available installations is provided by (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009), together with technical information regarding heat rate (energy input per unit of power produced), power efficiency (from 16 to 40%), gas flow and temperature, NOx and CO emissions.

2.1.2.1.2Fuel used

Natural gas represents the main fuel used for gas turbines. Biogas utilization in gas turbines is also possible, but, *ceteris paribus,* an additional amount of fuel supply has to be provided for accounting the loss in the biogas' lower calorific values (less than half f the natural gas, on average basis).

2.1.2.1.3Process efficiencies

Electrical efficiencies of gas turbines are plotted on Figure 2.4 depending on plant power output, from catalogue data (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009), respectively for micro (30-200 KW), small (500 – 3000) and medium (3000- 10000) size turbines. Thermal efficiency is also plotted. Regarding power efficiencies, significant variations exist between different producers and brands, for all the sizes of plants considered. Variable-speed micro-turbines present higher efficiencies (26-31%), while fixed speed, medium sized installations present the lowest ratios on average, especially when compared with larger plants which represent the best performers. As expected, no trend in thermal efficiencies is noted for micro-turbines for only which data has been available.

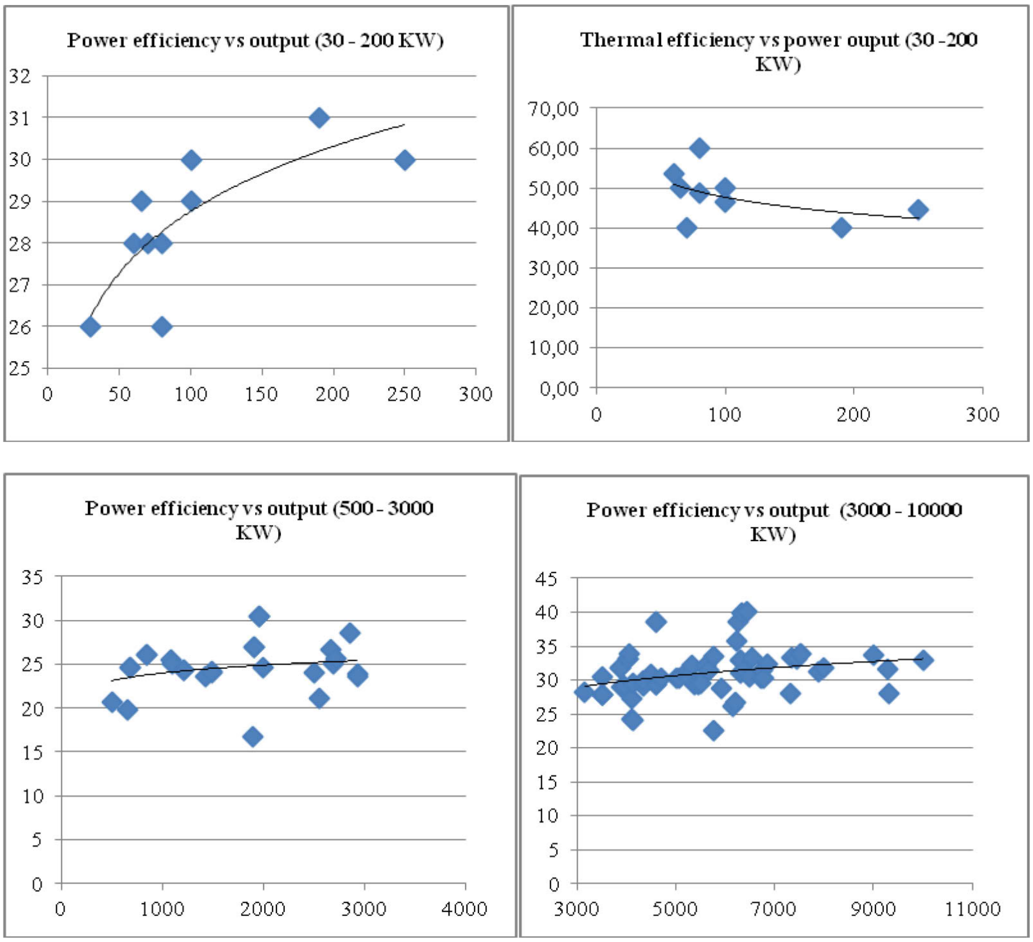


Figure 2.4: Power and thermal efficiency of gas turbines versus rated power output (kW)

Variation in operation like part load conditions or ambient temperatures influence power output, for the same reasons discussed for ICEs. (US-EPA, Technology Characterization: Gas Turbines, 2008) Similarly, altitude influences performance variation of gas turbines.
Micro-turbines, given their capacity of working with variable speed, present more flexibility in load variations, leading to limited efficiency reduction due to part load operations. Variation in part-load efficiency has been reported by (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009) and (US-EPA, Technology Characterization: Gas Turbines, 2008)

2.1.2.1.4Maintenance required

Generally, small/medium size turbines are reliable machines with low maintenance requirements, mainly due to the limited amount of moving parts. Periodic inspection is carried out after 4000 operating hours involving filters substitution, bearings inspections for vibration reduction and fuel consumption monitoring. Major overhaul is needed after 25.000 – 50.000 hours, for upgrading components and checking turbine/compressor's blades and seals. Micro-turbines maintenance schedule, provided by (US-EPA, Technology Characterization: Gas Turbines, 2008), includes:

- After 8.000 hours: air and fuel filter replacement;
- From 16.000 to 20.000 hours: fuel injectors, igniters and thermocouples inspection;
- After 20.000: battery replacement (only for stand-alone units);
- After 40.000: major overhaul

Such relevant performances in terms of low maintenance needed, makes gas turbines suitable for long-term operations, allowing, for base-load operations, system availability higher than 95%, as reported by the previous source

2.1.2.2 Economic considerations

Investment, operating and maintenance costs are assessed in the following paragraphs. Investment costs will account for both turbine-only and complete CHP package, depending on plant size, while operating costs will consider basically fuel consumption. Eventually, maintenance cost will be assessed depending on operating hours and service required.

2.1.2.2.1Investment costs

A preliminary distinction has to be considered for micro-turbines and conventional small/medium size gas turbines. The former, working at lower temperatures, require less expensive materials (steel rather than ceramics) and does not present intermediate cooling system like larger size's one. Single-stage compressors also represent a reduction in micro-turbine total costs. On the opposite, scale economies and frequency adjusting for variable speed operations increases micro-turbines 'costs on a relative basis (€/KW) than larger size's one. (US-EPA, Technology Characterization: Gas Turbines, 2008) identified the following main items in small and medium size turbines costing.

- Equipment (Turbines, electrical equipment, fuel system, water treatment, heat recovery), accounting for 59% of total costs;
- Construction, 20%;
- Other Costs (Project Management, shipping, developing fees, contingencies, financing), 21%.

Elaboration on the same data allowed to compute plant specific costs (expressed in 2007 k$/KW) of plants ranging from 1MW to 45 MW, as plotted on figure 2.5. A similar trend is reported by (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009) and expressed in 2008 €. Both trends shows that gas turbines price is mainly driven by additional equipment such as heat recovery, fuel injectors account for most of the expenses, especially for small size plant (< 1MW), while, increasing power output, price tends to stabilize to 1500-1000 €/kW.

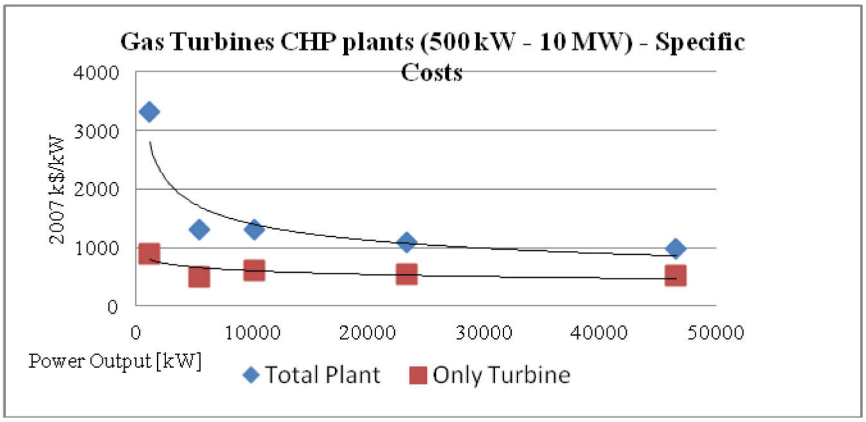


Figure 2.5: Gas Turbines CHP plant costs

Regarding micro-turbines turn-key installation costs at 1000/1500 €/kW have been reported (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009). (US-EPA, Technology Characterization: Micro-Turbines, 2008) quotes CHP-plants based on micro-turbines (30 – 250 KW) costing from 2.970 to 2.440 $/kW, plotted on figure 2.6.

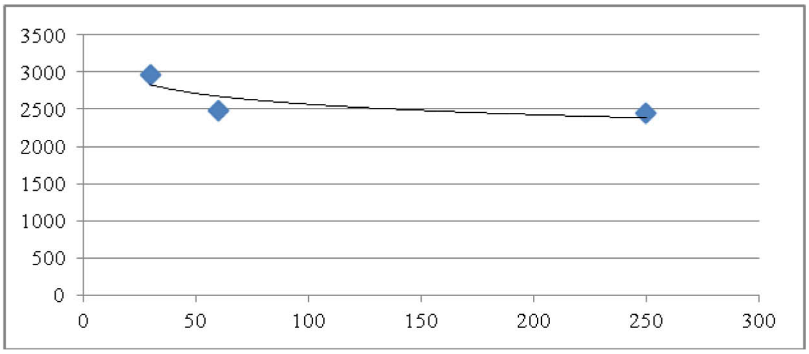


Figure 2.6: Gas Turbines CHP plant costs

2.1.2.2.2Maintenance costs

Regarding small and medium-size turbines, full service maintenance costs have been provided by (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009), varying from 0.7 c€/kWh to 0.4 c€/kWh, depending on plant size, while similar trend in maintenance costs have been provided by (US-EPA, Technology Characterization: Gas Turbines, 2008), ranging from 1.1 to 0.42 c$/kWh, as shown on figure 2.7 and table 2.2.

Table 2.2: Operations and Maintenance Costs of Gas Turbines (30 – 250 kW)

MT size [kW]	30	65	250
O&M Costs – Full Service Contract [c$/KWh]	1.5 – 2.5	1.3 – 2.2	1.2 – 2

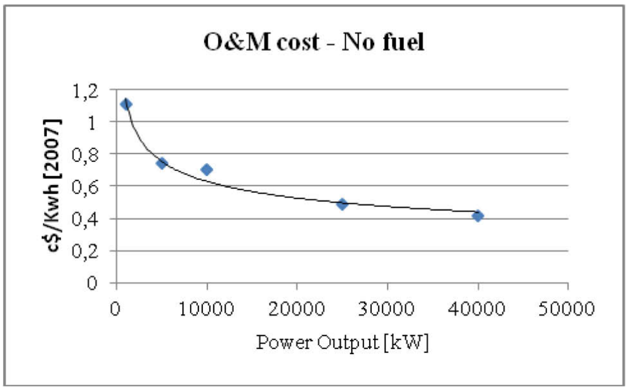


Figure 2.7: Operations and Maintenance Costs of Gas Turbines (500 – 40.000 kW)

2.1.2.3 Environmental considerations

As previously outlined for internal combustion engines, environmental performances of gas turbines depends on specific fuel used, combustor type and fuel gases treatment. Referring to turbines emission, conventional unit of measurement used are unit of mass (usually mg) over energy, the latter expressed in terms of input energy (kWh_c) or output power (kWh_e).
Reducing NO_x emissions in gas turbines is usually done by wet treatments; dry treatments, ultra-low emissions catalytic system. A taxonomy for characterizing turbines emissions has been provided by (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009). Variations of three orders of magnitude exist between ultra-low emissions turbines and conventional turbines. Assessing the data available on emissions provided by constructors – which presents the limits previously outlined for ICEs – emission trends for NO_x emission range from 140 to 180 mg/kWh_c. Other pollutants derive from un-burnt hydrocarbons, volatile organic compounds, sulfuric compounds and particulates. PM and SOx strictly depends on fuel features, being about null in natural gas-fed system, while hydrocarbons emissions, for micro-turbines range from 5 to 9 ppmv (US-EPA, Technology Characterization: Micro-Turbines, 2008).

Eventually, gas turbines are designed for reducing emissions at full load operations. Variation in these parameters greatly affects turbines' emissions which have been assessed by (Canova, Chicco, Genon, & Mancarella, 2007). As power load diminishes, NO_x, Total Hydrocarbons, CO and Non-Methane Organic Compounds,

2.1.3 Fuel Cells

Despite their little utilization, fuel cells present a potential in CHP applications due to their intrinsic advantages of modularity, power efficiency at full and partial load, and environmental benefits. However, technical complications and still-high investments costs limit their diffusion, together with maintenance requirements. Technological, economic and environmental issues will be considered in the following paragraphs.

Energy conversion of fuel cells, differently from the technologies previously assessed, exploits electrochemical reactions in order to convert the chemically-bound energy of a fuel, typically hydrogen. If this fuel is not readily available – as most of the cases – it has to be produced by reforming hydrocarbons (mainly natural gas), which requires an additional energy input to the system, and therefore lower efficiencies. Various cells properties have been reviewed by (US-

EPA, Technology Characterization: Fuel Cells, 2008) and (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009). Eventually, direct current has to conditioned to be suited for external use. Therefore electronic rectifiers and frequency-adjuster has to be used and designed for this purpose. Depending on the electrolyte, temperatures, ions exchanged, process efficiency and losses vary, accorging to the details provided in the following sections.

2.1.3.1 Technical considerations

The intrinsic features of fuel cells in terms of construction and modularity, together with the relatively recent utilization in commercial uses and the great variations in cell type, makes really difficult to standardize fuel cell performances. For this reason, the main parameters considered in the following analysis will be based on real case applications derived from external references.

2.1.3.1.1Commercial size available

One of the main advantages of fuel cells consists in their modularity and the possibility of working in series without affecting whole system's performances in terms of efficiencies. However, commercial shows ranges of power output available from manufactures is limited to relatively few models, from few kilowatts to 1 MW.

2.1.3.1.2Fuel

Hydrogen production has to be provided for fuel cell operation. Such fuel may derived from refinery/gassification processes or, as mostly used, from reforming of hydrocarbons, namely natural gas, due to its diffusion, coadiuvated by catalyst action. Regarding potentially pollutant substances which could compromise FC usage, Sulfur, together with carbon monoxide, represents a major contaminant for fuel cells, especially low-temperature ones, which have sensitive catalyst (platinum).

2.1.3.1.3Efficiencies

Power production efficiency represents one of the main advantage of fuel cells, as reported in (US-EPA, Technology Characterization: Fuel Cells, 2008). Efficiencies up to 60% may be achieved by a broad range of plants varying from small capacities to larger plants. An extrapolation of the commercial data available (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009), confirm such results in Figure 2.8.

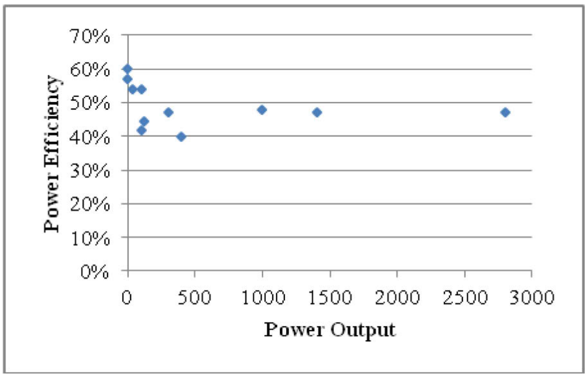


Figure 2.8: Power efficiencies of Fuel Cells

Regarding efficiencies's variation on part-load operations, fuel cells presents the great advantage of maintaining rated performances even at limited loads (up to 50%). (US-EPA, Technology Characterization: Fuel Cells, 2008) benchmarked fuel cell part-load operations with ICE's, while (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009) showed an even-increased efficiency on part-load operations of fuel cells. Regarding the quality of the heat recovered, operational temperatures from manufacturers show that the low temperature cells (PEM) are suitable for hot water heating (60-80°C), while PAFC and AFC allows higher temperatures up to 120°C. MCFC and SOFC, given their relevant operating temperatures, are suitable for high-quality heat recovered and steam production up to 10 bar, suitable for both environment and process use.

2.1.3.1.4Maintenance

Typical routine maintenance operations (US-EPA, Technology Characterization: Fuel Cells, 2008) of fuel cells involve replacement of air/fuel filter and reformer igniter or spark plug, water treatment beds, gaskets, valves and electronic components. The time-frame for these operations ranges from 2000 to 4000 hours.

Major overhaul refers to:

- Shift catalyst replacement (3-5 years);
- Reformer catalyst replacement (5 years);
- Stack replacement (4 – 8 years)

The variability in maintenance operations depends on plant operations and stresses, especially deriving from impurities in fuel which can damage catalyst and compromise electrolyte efficiency. Applications of fuel cells as premium power systems reached system availability from 94 to 96.3%, but the possibility of paralleling fuel cells without affecting power efficiencies (given the considerations of the previous paragraph) allows reaching higher availability factor.

2.1.3.2 Economic considerations

The economic assessment of Fuel Cells should consider the detailed of plant installations and the specific type cell utilized. Given the recent commercialization of fuel cells, costs provided the following analysis should be considered only as a general trend, while direct quotations should be used for more detailed assessment. However, the following section will provide a general order of magnitude of investment, maintenance and operating costs.

2.1.3.2.1Capital costs

The two previous sources have also computed the total costs of fuel cell plants depending on plant size and cell type. On relative terms, the repartition of initial costs is mainly due to total equipment (85%), while labor/material (7.6%) and engineering/management (7.5%) fees share for the remaining quota. On absolute terms fuel cell capital costs have been assessed by the same authors, while specific plant costs – depending on plant size - have been elaborated and reported on figure 2.9a and 2.9b. Total costs ranging from 2000 to 4000 €/kW have been identified for EU standards, while overseas source accounts for higher capital costs, ranging from 4500 to 8000 $/kW.

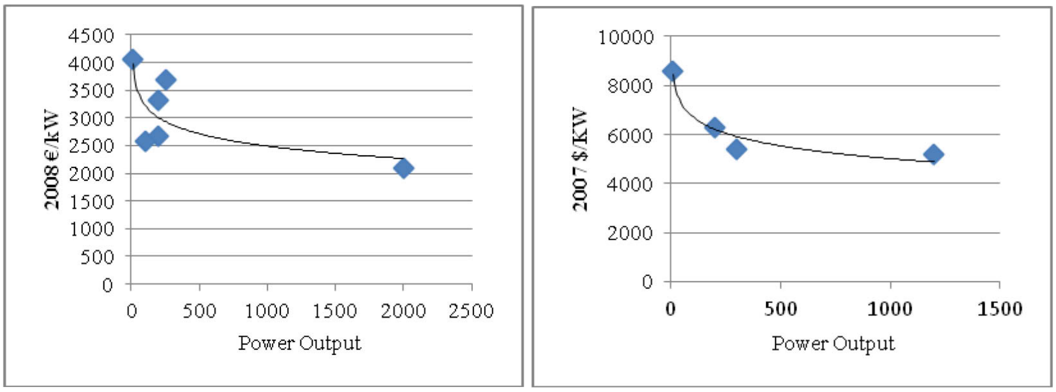


Figure 2.9:Fuel Cell equipment costs

2.1.3.2.2Maintenance

Maintenance costs for fuel cells present the same uncertainty explained for capital investment. However, broad figures have been provided by (US-EPA, Technology Characterization: Fuel Cells, 2008) accounting a 0.7 to 2 c$/kWh, excluding the stack replacement costs. (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009) provided similar data for EU context, identifying both costs for routine and minor overhaul operations only (blue dots) and total maintenance (including stack replacement). Routine maintenance costs presents a stead logarithmic downward trend (figure 2.10) respect to plant size, while total maintenance, including major overhaul, present a more irregular trend.

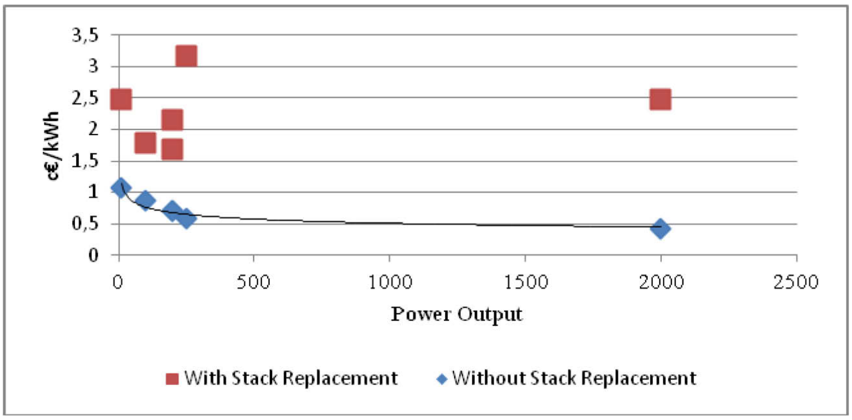


Figure 2.10:Fuel Cell Maintenance Costs

2.1.3.3 Environmental considerations

Due to their intrinsic operations, involving electro-chemical oxidation rather than combustion, fuel cells presents the lowest environmental emissions among fossil-fuel energy systems. Main emissions depends on the fuel pre-treatment (the reforming process and the anode oxidation), which is however a lean oxidation (8-15% H_2 percentage), allowing both carbon oxidation and little thermal NO_x formation. Excessively lean processes may lead to partial combustion and CO/VOC formation. Sulfur emissions are basically zero, because of the previous considerations on the need of sulfur-free fuels for FCs. Regarding CO2 emissions, on an absolute scale hydrogen electro-chemical conversion would not produce any CO2, but, given that the hydrogen is mainly produced by carbon-based fuels, the amount of carbon dioxide released depends on the process used for hydrogen production. Steam reforming process, as the previously described, produces one mole of CO2 for each mole of CH4 treated. Gasification or pyrolytic processes would allow to both produce hydrogen gas and fix the carbon content in liquid or solid matrices, but they are usually preferred for more carbonaceous fuels like coal. Little data provided by constructors on emissions from fuel cells, accounting from limited NOx emissions (less than 0.02 lb/MWh, equal to 9 mg/kWh) and negligible amounts of other pollutants such as CO, VOC and PMs. Data from (Bianchi, Spina, Tomassetti, Forni, & Ferrero, 2009) shows higher values, ranging from 25 to 9 mg/kWh for NOx, 45 to 19.1 mg/kWh for CO and VOC limited to 4.5 – 5.5 mg/kWh.

2.1.4 PV Panels

Power production from solar energy has been consolidated worldwide as a renewable, affordable, reliable alternative for power production. However, the discontinuity of solar source make such plant unreliable for base-load industrial operations, making those plants suitable only as an auxiliary source, coupled to continuous power devices and grid connection.

2.1.4.1 Main principles

Solar radiation is composed by three components, i.e. direct (or "beam") radiation, resulting from the direct components of energy from the sun; diffused radiation, which depends on the deviations due to the atmospheric agents such as clouds, modifying solar beams directions; reflected radiation, due to the reflective properties of local surfaces. While beam direction can be considered mono-directional and dependent on direct exposure, diffused component is scattered and present multi-directionality; reflected radiation depend on reflective properties of surfaces, represented by the *albedo* value.

Photovoltaic plants convert solar energy (beam, diffused and reflected components) to power exploiting the semiconductor structure of photovoltaic modules, presenting drug semiconductors (Silica is the most used material) with electron free components which are activated by solar energy, allowing electrons movement and current flow. Current produced by such systems present variable frequency which has to be adjusted by electronic device (inverter) which may be installed o decentralized basis, or a single inverter might be used-

2.1.4.2 Technical considerations

Installing PV plants involves, from a strictly technical point of views, assessing at least the following features:

- Location
- Tracking system
- Module/inverter type and size
- Power conversion efficiency

The last two points will be assessed in the following paragraphs.

2.1.4.2.1Module and inverter type and size

Difference in semiconductors production and assembling influence PV panels performances. The most diffused panels are:

- Mono-crystalline: semiconductors cells are cut from a single crystal of silicon material, allowing a regular structure which favor electrons activation and movement

- Poli-crystalline: cells are cut from a block of silicon material consisting in multiple blocks of silica bonded to each other, leading to a more scattered cell structure and irregularities in electronic movement;
- Amorphous structure: non-crystalline structure is present in this type of cells, where a layer of silica material is placed on surface, allowing high flexibility in module placement, but lower efficiencies.

Module size ranges from few watts to 180-200 Watt per module.

2.1.4.2.2 Power efficiency, dimensions

Module power conversion efficiency depends on panel type, constructor, size, additional components, and year of installation. Mono-crystalline panels presents higher efficiencies than polycrystalline ones (13-17% vs. 12-13%), due to the more regular structure of the former. Amorphous panels instead present the lowest efficiencies, limited to 8-10%. However polycrystalline solutions are more efficient in capturing diffused radiation (most used in cloudy regions), while amorphous panels, given their flexibility and low-weight present the advantage of a wide range of applications for power production. Different PV panel manufacturers report varying efficiency for similar panels. A graph showing panels efficiencies for mono-crystalline and poly-crystalline panels from commercial catalogue of four of the major PV panels producers are reported on figure 2.11.

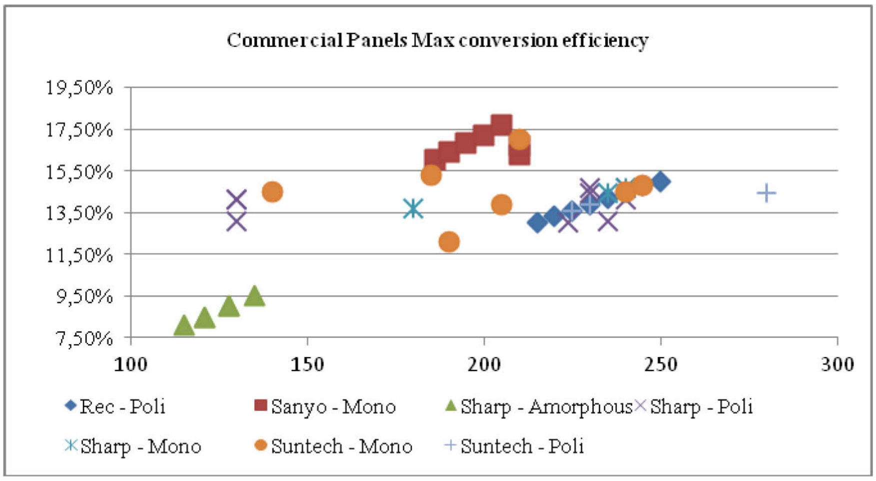


Figure 2.11: Efficiency of various types of PV modules

Given such variations in power efficiencies, the intensity of PV panels (peak kW per square meter) varies accordingly. On table 2.3, the range of variations in power intensity for amorphous, polycrystalline and mono-crystalline panels has been reported, calculated from the data available from panel's producers.

Power conversion efficiency is affected by many variables such as operating temperatures, type of radiation (direct vs. diffused), module type. Some producers guarantee absolute efficiencies losses of maximum 0.7% per year (on absolute terms), thus guaranteeing 80% of module efficiencies after 0 years of operations. Inverter efficiency ranges from 94 to 98%.

Table 2.3: Energy intensity of various PV panels

Panel type	**Panel Intensity Range [kW/m^2]**
Amorphous	60 – 90
Poli-crystalline	90 - 150
Mono-crystalline	110 – 170

2.1.4.3 Economic considerations

The economic assessment of PV plants is mainly referred to the capital costs of the plant, given that the operating costs of such system are limited to maintenance costs (surface cleaning) and insurance. Costs of PV panels are rapidly descending due to the presence of new actors in the market and the increased diffusion of PV modules. The costs of PV modules are also linked to that of Silica, even if such connections are currently being decoupled because of the diminishing in use of such raw material in panel production. On general basis, the capital costs of PV modules can be split up in 4 components

- Module;
- Inverter;
- Supporting structure and additional components (e.g. battery)
- Engineering and installation costs.

Module costs account for about 2/3 of total installation costs, with other quota referring to the remaining expenses. A trend in module costs is provided on table 2.4, for both EU and US area. (SolarBuzz, 2011) showing a sensibly decreasing trend in module price, equal for September 2011 to 2.43 €/W. Market research assessing the cost trend of module, depending on the type of technology (monocrystalline or polycrystalline) has not been found. However, a research of (SolarBuzz, 2011) shows that lowest multi-crystalline modules cost on average 10% more than monocrystalline ones (1.13 vs. 1.04 €/W). Yearly operating costs of PV plant, as previously said, are mainly due to insurance and maintenance expenditures. These values have been estimated from direct sellers as a percentage of total capital costs and accounts for 1% (insurance) and 0.3% (maintenance). Given the average investment costs of 3000 €/kW$_p$ (A) and the producibility of about 1100 kWh/kW$_p$ (B), maintenance and insurance costs of PV plants amount to about 3 c€/kWh (A*0.013/B).

Table 2.4: PV panels capital costs from 2010/2011 (source: Solar Buzz Market Research)

	Unit	Sep 10	Oct 10	Nov 10	Dec 10	Jan 11	Feb 11
Module	US$/Wp (≥125 W)	$3.61	$3.59	$3.51	$3.47	$3.38	$3.29
	Euro€/Wp (≥125 W)	€3.23	€3.20	€3.19	€3.09	€3.05	€2.90
Inverter	US$/Continuous Watt	$0.715	$0.715	$0.715	$0.715	$0.715	$0.715
	Euro €/Continuous Watt	€0.558	€0.522	€0.508	€0.543	€0.537	€0.522
Battery	US$/Output Watt Hour	$0.207	$0.207	$0.207	$0.210	$0.210	$0.211
	Euro€/Output Watt Hour	€0.161	€0.151	€0.147	€0.160	€0.160	€0.154
		Mar 11	Apr 11	May 11	Jun 11	Jul 11	Aug 11
Module	US$/Wp (≥125 W)	$3.19	$3.12	$3.11	$3.10	$3.02	$2.84
	Euro€/Wp (≥125 W)	€2.80	€2.73	€2.69	€2.66	€2.54	€2.51
Inverter	US$/Continuous Watt	$0.715	$0.715	$0.715	$0.715	$0.715	$0.714
	Euro €/Continuous Watt	€0.515	€0.508	€0.479	€0.500	€0.500	€0.500
Battery	US$/Output Watt Hour	$0.212	$0.212	$0.213	$0.213	$0.213	$0.213
	Euro€/Output Watt Hour	€0.153	€0.151	€0.143	€0.149	€0.149	€0.149

2.1.4.4 Environmental considerations

Exploiting the solar radiation to produce energy is logically a zero-emission solution. However, a complete LCA assessment of PV modules should take into consideration all the environmental impacts due to the silica purification processes (from carbonated components in electric arc furnaces), doping and module assembling. However, such impact has not been considered at this stage.

2.1.5 Benchmarking technologies for industrial use

A benchmark for comparing the various technologies is now provided, later summarized on table 2.6 and. 2.5

a) **Fuel used:** Internal combustion engines provide a broad range of fuel to be used, from gaseous (natural gas, biogas, LPG) to liquid fuel (diesel, biodiesel, bio-oil), also in dual fuel solutions, allowing a high flexibility. Gas turbines and micro-turbines generally use biogas or natural gas as main energy source, while hydrogen reforming from natural gas represents the main energy source of fuel cells.

b) **Available plant size**: given the diffusion of ICEs as both stationary and mobile energy sources, a broad range of power sizes is available on the market, for both liquid and gaseous fuels. Similarly, gas turbines are broadly used in commercial applications, therefore a range of plants is available worldwide for stationary applications related to the industrial industry. Microturbines operate in ranges from 30 kW to 250 kW, with higher potentialities to be reached by modular installations. Fuel cells are very limited in use, thus commercial applications refers to civil scale (1-2 kW) to some industrial installations (100 – 1000 kW). Modularity of PV panels allows broad plant ranges, limited by the availability of room for plant installation

c) **Specific capital costs:** The assessment of capital costs is strictly related to site-specific conditions, which in turn affects engineering, building and transportation costs, and commercially available dealers and dealing power.

d) **Power conversion efficiencies**: ICEs, especially for large size, provide power conversion efficiencies over 40%, sensibly decreasing below 20% for smaller civil applications. However, sensitive differences exist between various producers. Micro and Medium/Large size Gas Turbines present low efficiencies (about 30%), while fuels cells have achieved the highest conversion efficiency ranging from 47 to 55% .

e) **Maintenance costs**: maintenance costs highly affects capital return of investment and are strictly related to the specific plant operating conditions (e.g. on/offs , rotating speed, part load operations).

Table 2.5: CHP technologies benchmark

Technology	**ICE**	**Gas Turbines**	**Micro-turbines**	**Fuel Cells**	**Solar PV**
Fuel	Liquid, Gaseous	Gaseous	Gaseous	Mainly Gaseous	-
Size Availability	Excellent (from 1 kW to 8 – 17 MW)	Very good (from 500 kW to 10 MW)	Limited (30 – 250 kW)	Medium (1 to 1400 kW)	Excellent
Capital costs	2000/3000 (< 60 kW) , 1000/ 2000 (60 kW to 1 MW) 700 – 1000 (> 1MW)	1000 – 1500 €/KW	2000 – 3000 €/KW	3000 – 4000 €/kW	3000 – 3500 €/kW
Power conversion efficiency	40% (> 1MW)	30%	30%	47-50%	3000 – 3500 €/kW
Maintenance	2-3.5 c€/kWh (< 1MW), 1.5 c€/kWh (> 1MW)	0.5 – 0.7c€/kWh	1.5 c€/kWh	3.5 – 4 c€/kWh	3 - 3.5 c€/kWh (depending on insurance)

f) **Emission rates**: specific emissions rates might be expressed in terms of concentrations (e.g. mass per Nm3, ppm) or related to the output (mg/kWh) or input (mg/MJ), as found in this chapter. This latter unit has also been used as the reference standard in the AP-42 emission factor database related to stationary energy sources, from which the emission rates of ICEs (Natural Gas and Diesel), GT have been found. Bio-Oil ICEs emissions have been calculated considering the variation in emission as computed in (US-EPA, A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, 2002), while MT and FC emission rates have been taken from technology assessments of US-EPA previously described. Generally, ICE presents higher emission rates (especially diesel-fuelled ones), followed by Turbines and Fuel Cells, which both presents emission rates at least one order of magnitude inferior than ICEs.

Table 2.6: CHP emission factors (elaborated from US-EPA, AP42 standards)

Technology	**NOx**	**CO**	**SO2**	**NMVOC**	**PM 10**
	g/MJ	**g/MJ**	**g/MJ**	**g/MJ**	**g/MJ**
Natural Gas ICE	9.50E-01	1.60E+00	2.53E-04	1.27E-02	4.08E-03
Diesel ICE	1.90E+00	4.08E-01	1.25E-01	1.37E-01	1.33E-01
Bio-Oil ICE	2.09E+00	2.16E-01	0.00E+00	1.37E-01	7.06E-02
Fixed-speed Gas Turbines	2.53E-01	6.84E-01	0.00E+00	0.00E+00	0.00E+00
Variable Speed Microturbines	1.38E-01	3.53E-02	3.40E-03	9.03E-04	2.02E-03
Fuel Cell	9.92E-03	1.19E-02	0.00E+00	3.40E-03	0.00E+00

2.2 Environmental background

In this section the main environmental impacts of the previously described technologies will be considered. The analysis will firstly focus on the major categories of pollutants to be assessed while considering local impacts assessment on quantitative basis, assessing formation processes and toxicology, and will then asses the methodologies for impacts assessment.

2.2.1 Emission assessment: macro-toxicants

Macro-toxicants are defined as such compound which presents toxicology effects only with high dosage and/or long term exposure for both human and ecosystems. In this category, emissions of Nitrogen Oxides, Carbon Monoxide, Sulphur Dioxide and Particulate Matter will be further treated.

2.2.1.1 Nitrogen Oxygen (NOx)

The category of NO_x encompasses elements combining Nitrogen and Oxygen, mainly in the forms of nitric oxide (NO), nitrogen oxide (NO_2) or nitrous oxide (N_2O). The formation of NO_x mainly depends on oxidation processes such as stationary or mobile combustion. Combination of reaction temperature and reagent concentration highly affects NO_x production. At least three types of NO_x may be identified:

- Fuel NO_x, which are caused by the presence of fuel bound Nitrogen (FBN) which, reacting with comburing oxygen, produced NO_x;
- Thermal NO_x, which, especially at high temperatures, are caused by the breakdown of air nitrogen which reacts with comburing oxygen;
- Prompt NO_x, which are caused by the reaction of fuel hydrocarbons with atmospheric hydrogen leading to organic compounds (CN, NH, HCN) which are in turn oxidized to NO/NO2.

Toxicity of NO_x to both human and eco-system has been broadly studied. (Shugart, 2005) reviewed NOx effects referring that a 10 ppm for 10 minutes exposure would lead to coughing, chest pain and difficulty in breathing, with higher concentration leading to skin corrosion. Long term exposure might lead to respiratory infections, pulmonary edema and lung disorders. Eco-toxicology of NO_x relates to numerous effects such as acid rain formation, caused by the reaction with air's humidity leading to the formation of nitric or nitrogen acids (HNO_3, HNO_2) and leading to the formation of excessive algal population (eutrophication), as well as catalyzing ozone formation at atmospheric level leading to photochemical smog issues.

2.2.1.2 Sulphur Dioxides (SO_2)

Sulphur Oxides are caused by the oxidation of sulphur with oxygen, mainly in combustion processes. The formation of sulphur dioxide is caused by the presence of sulphur in the combustion fuel, leading to the formation of SO_2, which oxidizes to SO_3 at atmospheric conditions. Sulphur-rich fuel like coal represents the main source of sulphur dioxide emission worldwide, while percentages of sulphur in fuel-oil or diesel products are rapidly diminishing due to National and International regulation and standards.

Human toxicity of SO_2 exposition, as reported by (Gad, 2005) causes eyes irritation, and respiratory tracts, particularly effecting asthmatic individuals. Extended exposition to SO_2 has not been clearly reported as more serious damages to human health (i.e. cancer). Similarly to NO_x, SO_x reaction with water air causes sulphuric acid formation leading to the so called phenomenon of "acid rains".

2.2.1.3 Carbon Monoxide (CO)

Carbon Monoxide derived from the partial combustion of fuel-bound carbon, due to limitations in air presence or fuel presence/mixing. The formation of CO is directly linked to that of thermal NO_x. In fact, the excess air needed for complete oxidation of carbon lead to a temperature decrease which in turns affects (increases) NO_x formation. On the other side, increasing combustion temperatures (by means of increasing fuel usage or limiting excess air) would increase NO_x formation but would lead to increased amount of CO, keeping in mind the relevance of excess air in NO_x formation previously described.

Human toxicity of CO has been reviewed by (Stork & Anguish, 2005), reporting both short term and long term exposure effects. Carbon monoxide toxicity is due to its reaction with blood hemoglobin leading to the formation of Carboxyhemoglobin (COHb) which transport CO through the blood stream, reducing the amount of oxygen (*anoxia*) or binding to blood cells.

2.2.1.4 Particulate Matter (PM)

This category encompass a series of pollutants composed by exhausted fly ashes, road dust, mineral, etc. combining both organic and inorganic compounds which are broadly categorized depending on particle size, with the common measures referring to particles with a diameter less than 10 µm (PM10) and 2.5 µm (PM2.5). Defining the effects of such pollutants depends on site specific features and cannot be generalized. Extended studies have been conducted on diesel-fuelled vehicles' PM emissions leading to respiratory effects, irritation, asthma, while eventual extended exposure may lead to more serious damage (as cancer) even if such correlation has not been completely confirmed yet, as reported by (Wurzel, 2005)

2.2.2 Micro-Toxicants

Micro-toxicants are defined as compounds whose production is generally limited but whose toxicity is high even at low concentration/exposures. Given such features, the control of such compounds is particularly difficult, and relates to emission of Volatile Organic Compounds (VOCs), Polycyclic Aromatic Compounds (PAHs), Metals and dioxins/furans.

2.2.2.1 PAHs

In this category a broad range of Polycyclic Aromatic Hydrocarbons (PAH) is considered. PAHs, which are chemical compounds characterized by aromatic rings (generally hydrogen) which bounds with organic material leading to a highly persistent compounds, which accumulates in human and animal organisms. PAHs occur in incomplete combustion of fossil fuel, tars and chars in various forms depending on chemical structure of the compounds. Most relevant PAHs are benzenes, Pyrenees, toluene, styrene and related compounds such as benz(a)anthracene, benz(a)pyrene, benz(e)pyrene, etc. The toxicity of such compounds highly varies among PAHs, some of them are recognized carcinogens to both skin and lungs in case of extended exposure, while short term exposure may lead to skin and eyes irritation.

2.2.2.2 VOCs

Volatile Organic Compounds (VOCs) are substances which evaporate at conditions. This group of chemicals is broadly used as solvents in paints/varnishes in order to promote pigment dilution, but also in disinfection and adhesive materials and includes some PAHs such as toluene and benzene. Other most common VOC are acetone, ethyl acetate, Acetaldehyde, Ethanol, Hexane and Methane. This last gas, given the common use as fuel, may be excluded in VOCs accounting, thus a common measurement is called Non-Methane Volatile Organic Compounds (NMVOCs)

Toxicity of VOCs, as reported by (Anand & Mehendale, 2005), is greatly affected by specific VOC features such as number of carbon atoms, saturated or non saturated conditions, chain structure. Short term exposure may lead to eye and respiratory tract irritation, headaches, dizziness, visual disorders, and memory impairment, while long-term effects like cancer and mutagenesis are well-documented for Vinyl Chloride and benzene long term exposure.

2.2.2.3 Metals

While essential for routine metabolic reactions, some metals present biochemical features which may lead to bio-accumulation and eventual human toxicity. The major route for metal assumption is ingestion, given the bio-accumulation of some of the speciation in food. Again, metal speciation is fundamental in identifying toxicity features. Species of arsenic, lead, nickel, cadmium and chromium have been found as documented carcinogens.

Other potentially toxic micro toxicant releases regards to dioxins and furans (Poly-Chloro(di)benzo-Dioxins/Furans, PCDD/Fs). Such toxicants are mainly made by carbon and chloride atoms, which presents both short term and long term toxic effects whose dangerousness depends again depends on toxic speciation.

2.2.3 Environmental Impact Assessment

Environmental Impact Assessment represents one of the stages of the Life Cycle Assessment of a product/process, as presented on section 1.3.2. After having quantified the physical flows of the system (Life Cycle Inventory), the goal of the life cycle impact assessment consists in determining the impacts that such flows generate to the different stakeholders considered in the evaluation process, while assessing different forms of impacts. Generally, different impact categories are linked to specific reference area (defined as “compartments”), such as air, water, soil and resource consumption. Some type of pollutants impact simultaneously on more than one category, therefore each LCIA methodology consider in a different way. LCIA methodologies have been reviewed by (Hischier, et al., 2007), and a synthesis of them has been reported on Appendix A, together with a brief analysis of their relative advantages and disadvantages.

2.2.3.1 ECO-INDICATOR

Among the different LCIA methodologies, Eco-indicator 99 is a “damage-oriented” which, in the author’s opinion, allows a more comprehensive analysis of environmental impacts. Specifically, the Eco-Indicator methodology (Goedkoop & Spriensma, 2011) allows expressing the environmental impacts in three major categories:

- *Human Health*:
    - Damages caused by carcinogens substances;
    - Damages caused by organic substances;

  - Damages caused by respiratory effects;
  - Damages caused by climate change;
  - Damages caused by ionizing radiations;
  - Damages cause by ozone depletion;
- *Ecosystem quality*:
  - Damages caused by toxic emissions;
  - Damages caused by acification/eutrophication effects;
  - Damages caused by territory occupation and conversion;
- *Resources*:
  - Damages caused by mineral extraction;
  - Damages caused by fossil fuel extraction;

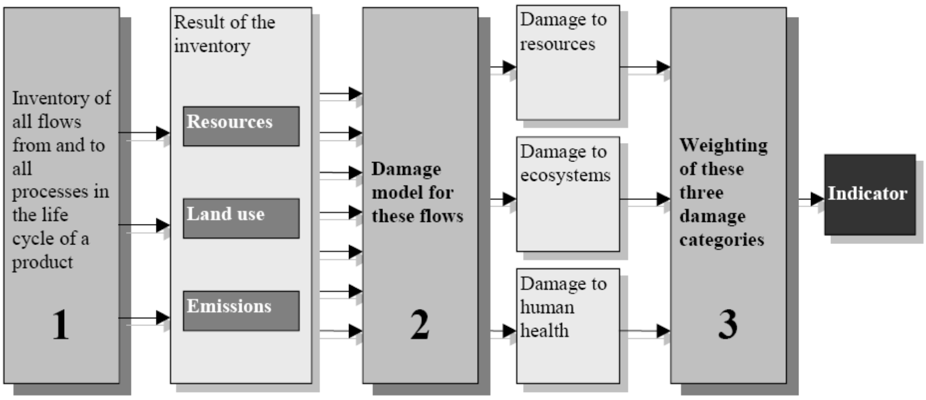


Figure 2.12 –Eco-Indicator methodology. Source:: (Goedkoop & Spriensma, 2011)

A synthesis of the Eco-Indicator methodology – and generally a LCA approach – is provided on Figure 2.12, while different impact category will be assessed shortly, and consists of three main steps:

1. Damage Characterization;
2. Damage Normalization;
3. Damage Weighting;

Damage characterization consists in calculating the effects of pollutants emissions referring to the impact category previously described, while the weighting stage consists in normalizing the values previously calculated to a generally site-specific (i.e. average Europe concentration) value, while the weighting factors, without entering much into details about those, consists in choosing what type of effects consider or nor in the assessment (i.e. limiting the assessment only to scientifically demonstrated effects or broadening the view to potential effects yet-to-be-demonstrated. The first step (damage characterization) will be assessed in detail.

2.2.3.1.1Human Health damages

Damages caused by substances impacting on respirations (organics and inorganics), carcinogenics, climate change, ionizing radiations and ozone depletion are assessed in this category. How to assess such damages represents a key innovation in the eco-indicator methodology, which utilizes the concept of DALY (Disability Adjusted Life Years) as the main element to evaluate the impact on human health of different pollutants emissions in the various compartments. Following to the theoretical basis provided by (Huijbregts, et al., 2000), and adopted by the "World Health Organization" (WHO) and by the "World Bank", the concepts of DALY unifies the various effects leading to death or sickness. Effects leading to death are expressed by the indicator YOLL (Years Of Life Lost), which includes lethal effects such as tumors or respiratory effects. Death due to the latter are further divided into sudden and chronic effects.

The concepts of DALY also include non-mortal effects such as pathologies induced by pollutants emissions which contribute to reducing life quality, by means of the indicator YLD (Years Lived Disabled). DALY is thus calculated as a sum of these two indicators:

$$\text{DALY} = \text{YOLL} + \text{YLD} \qquad (2.1)$$

The process of calculating these two indicators consists in four steps:

- *Fate analysis*: linking the point emissions to the variations in concentration of the substances in a definite lifetime;
- *Exposure analysis*: linking pollutants concentration to exposure dosage, i.e. the quantity assumed by human bodies by various means of collection (respiration, ingestion, ecc.);
- *Effect analysis*: linking the dosages to the effects produced, i.e. cancer type, respiratory damages, relying on WHO databases;
- *Damage analysis*: linking the effects to the DALY number, firstly calculating YOLD e YOLL.

For example, the impact on human health of macro-toxicants, considering the hierarchical perspective (considering only effects with scientific consensus over them) and the DALY unit of measurement for normalized damage calculation is reported on table 2.7.

Table 2.7: Impact factor of Macro-Toxicants

	DALY/kg	Category	Emission compartment
NOx	5.76 E-3	Respiratory Effects	Air
Sox	3.55 E-3	Respiratory Effects	Air
CO	7.31 E-7	Respiratory Effects	Air
PM 10 PM 2.5	2.44 E-2 4.55 E-2	Respiratory Effects	Air

2.2.3.2 Eco-system damages

Ecosystem damage is calculated as the percentage of flora to be disappeared because of a variation of the environmental condition. Such indicators, therefore represents an effective way to evaluate bio-diversity. The unit of measurement is expressed in "PDF*m^2*yr", where PDF is the Potentially Disappeared Fraction of plant species. In this category, for example, acidification or eutrophication effects are considered, on various geographical scales. Similarly to the previous paragraphs, the calculation of the eco-system damage consists in the following steps:

- *Fate analysis*: linking emissions and concentrations;

- *Effect analysis*: linking concentration to toxicity;
- *Damage analysis*: linking effects to the disappearance of vegetal species;

2.2.3.2.1Resource damages

In this category, mineral and fossil resources extraction is considered. Extraction, instead of being related to the amounts of resource *used*, is linked to quantity of resources *remaining*, while the damage is expressed in terms of energy surplus required for future extraction of minerals and fossil fuels, thus expressed as an energy unit of measurement (MJ in Eco-Indicator).

Resource damage calculation consists in two steps;:

- Resource analysis: linking resource extraction to concentration reduction;
- Damage analysis: linking concentrations reduction to energy surplus required for future extraction;

2.3 Normative background

Having defined the scope of the work by both a techno economic and environmental aspect, in this last stage the normative aspects are to be assessed. Specifically, this assessment will focus on renewable energy production and emission/immission reduction considering various scopes, i.e. on an International, European and National (Italian) scale.

A preliminary distinction has to be made between pollutants immission and pollutant emissions: the first concepts, immission (I) relates to the variation of any pollutant (*p)* concentration (C_p) in a defined environment; the second – emissions (E) – is referred to the output of particular process, which in turns affects environment status. Logically, emission and immission values are related: in other words, the immission of a pollutant *p* into an environment in a certain moment timeframe $t = i$, depends on the total emitted substances and the status of the environment e at t = i – 1, which can be written as:

$$I_p = \frac{\Delta(C_p)}{\Delta t_i} = \Delta C_{i-1} + f(E_p) \qquad (2.2)$$

Legislation affects both immission, concentrations and emissions. Immission depends on site specific conditions, which in turns relate emissions and concentrations. The legislator act at these two levels (emissions and concentrations) defining limits and standards for major pollutants as those previously outlined, while authorization for emissions on particular environment (immission) are allowed depending on each specific case (environmental impact assessment, EIA).

Eventually, incentives towards renewable energy usage, energy efficiency and emission reduction, which are the three main objectives of EU policy, as assessed later on the chapter – will be reviewed, focusing on the National applications of the Italian context.

2.3.1 International Legislation

Among the various environmental impacts – as those outlined in the Eco-Indicator methodology of section 2.2.3.1, climate change is by far the most publicly debated. The alleged causality between GHGs emissions and climate change has coped with ever increasing emissions of carbon dioxide, the most relevant output of combustion processes. On an international scale, the most relevant step related to GHGs emissions has been the Kyoto Protocol (1997).

2.3.1.1 Kyoto Protocol

Kyoto protocol represents the first international agreement on climate change, signed by over 160 countries during the COP3 conference of the UN on Climate Change and Global Warming. The agreement consisted in reducing GHGs emissions (CO2 and other five pollutants, such as CO and methane) of a global 5,2% compared to 1990's level, to be achieved before 2012. Economic mechanism for exchange of GHGs emission shares have been agreed on. Local reduction objectives have been selected for each of the ratifying countries. EU (and Italy) ratified the agreement on the 31st, May, 2005, aiming to reduce GHGs emission by 6.5% (Italy) even if such reduction, in 2010, was far to be achieved (Eurostat, 2010).

2.3.1.2 Other agreements Bali and Copenhagen conferences

Bali conference (2007) represented the first step for defining the “post-Kyoto”. As a matter of fact, it has been impossible to define a new set of rules and binding prescriptions on GHGs reduction, thus the main output of the conferences was limited to a “road map” to new formal negotiations to be held in 2012. The Copenhagen Conference (2009), even presenting a similar goal – defining new rules and prescription to strengthen Kyoto’s target - similarly failed due to the strong opposition of developing countries such as India and China.

2.3.2 EU regulation

International efforts have been translated on a European level by the development of specific regulation, in which the so-called “20/20/20 Directive” represents the main output, (December 2008). Such directive imposed – with regulatory binding limits – to the member states the adoption of measures in order to reduce GHGs emissions by 20% (compared to the 1990 levels), increasing energy production from renewable sources up to 20%, and reducing energy consumption by 20%, with all the objectives to be achieved before 2020.

European legislation, while providing country’s guidelines in order to achieve the communitarian goals, has also focused on emission and concentrations of pollutants as those presented on previous section. Particularly, la EU directive 2008/50/CE identifies the objectives of air quality, defining methods for evaluating, maintaining and improving the latter, promoting collaboration among EU countries. The directive particularly focus on air quality limits on concentrations of SOx, NOx, CO, Pb, PM10 and PM2.5, As, Cd, Benzene, Benz(a)pyrene and Ozone.

Regarding pollutants *emissions*, EU directive 96/61/CE, later updated by the 2008/01/CE, defined a range of activities which require particular authorization process (Integrated Environmental Authorization) and whose emission limits, regarding specific pollutants, have to be defined by single States. Activities subjected to the IPCC directive are, for example, energy industries (energy production, refineries, coke and coal gasification ovens), metals production and processing (metal ore roasting or sintering, pig iron or steel, ferrous foundries, smelters), mineral industries (cement clinker, asbestos, glass, ceramics), chemical industries (organic and inorganic), waste management and other activities (pulp and timber industries and others), with some of the activities to be subjected only over pre-defined throughput threshold. Such directives, also, identifies the pollutants which have to be subjected to monitoring and limitations, which, referring to air emissions, such as sulphur dioxide and other sulphur compounds, oxides of nitrogen and other nitrogen compounds, carbon monoxide, volatile organic compounds, dust and other compounds.

2.3.3 Italian Regulation

Italian legislation received EU directives, but specifying actions in order to achieve the tree main objectives of the previously assessed directive. Specific legislation has thus been developed for assessing:

- GHGs emissions and immissions;
- Renewable energy production;
- Energy efficiency.

The Italian incentives framework is briefly assessed, focusing on the sections which will be useful later on this work.

2.3.3.1 GHGs emissions, air quality and air emission monitoring

Referring to air quality regulation, limits of the Italian decree n.155 of 13/08/2010 directly relates to the previously described European directive. GHG and IPCC's regulated emissions require National legislation to identify emission limits for each of the sector identified by the directive. Such step was taken by the Italian d.lgs. 152/2006 ("Testo Unico Ambientale") and following updates, which, among the consistent amount of normative which is there reported, identifies the limits for toxicants emission (NO_x, SO_x, VOCs, ecc.) for plants of specific companies. Incentives

At the national level, international and European policies have been addressed by a series of mechanisms aiming to foster the achievement of the goals of renewable energy production, energy efficiencies and greenhouse gases reduction.

2.3.3.1.1Energy production from renewable energy

National incentives on renewable energy productions focus primarily on power and heat production. Referring to power production, different schemes of incentives have been developed, such as::

- CIP6 mechanisms, which represented the first system for renewable energy production, based on fixed incentives schemes;
- Green Certificates, evolution of the CIP6 mechanisms but considering market based schemes;
- Feed-In tariffs for Photovoltaic plants production, later applied to thermodynamic solar as well.

Currently-used mechanisms are detailed in the following sections.

2.3.3.1.2Green Certificates

The green certificates mechanism ("Certificati Verdi", CV) consists in a system similar to the stock-market. Fossil fuel energy users, above a certain threshold, are obliged to produce a quota of their energy by means of renewable sources, creating thus a "demand" for green energy, while the offer is created by renewable energy producers, which can sold their share to those producers impossibilitated to satisfy their quota with internal resources. A central manager ("Gestore dei Servizi Elettrici", GSE) regulates this market, and represents the point of reference for determining the price of the certificate.

In January 2011, GSE communicated the price of CV as 87,38 €/MWh as a difference between:

- A reference value, equal to 180,00 €/MWh;
- The average yearly power selling price, defined by the Energy authority, and equal to 92,62 €/MWh

This system is not compatible with other forms of incentives (see later) or other contribution for capital expenditures. The later National Decree of 18/12/2008 ("decreto rinnovabili") modifies some of this benefit scheme, by modifying the following points :

- Incentive duration;
- Comprehensive Tariff Option;

- Diversified coefficient per source;.

Plant reported on Table 2.8 can receive CV for 15-year period, while for a particular class of plants (Power Production below 1MW) it is possible to choose a "Comprehensive Tariff" which consists in a fixed tariff of 0.28 €/kWh produced, without considering any further benefits such as excessive power sold to the grid. Each of the different type of plants, furthermore, access to a different incentive, by the introduction of a coefficient α aimed to promote some of the technologies rather than others, also reported on Table 2.8

2.3.3.1.3The "Conto Energia"

The "DM 181 of 28/07/2005, established the first framework for incentives to the solar power production by means of PV plants. Given the high success of this decree, on 2006, a second regulation has been emanated in order to amplify the capacity of the feed-in incentives scheme, from 100 MW to 500 MW. The DM 6/02/2006 thus introduced a national PV incentive scheme basing on *fed-in tariff*, i.e. providing a fixed amount of money for each kWh produced by the plant. The duration of such incentive is 20 years and its values have been distributed depending on power installed and also location. The DM 5/5/2011, eventually defined the most recent scheme on PV plants, by modifying the amount of the incentive and defining new conditions for accessing to it, with different incentives for

- Building-installed plants;
- Integrated PV plants with innovative features;
- Concentrations PV plants.

Table 2.8: Coefficients used for increasing the calculation of green certificates

Plant Type	α
Wind Turbines Onshore > 200kW	1
Wind Turbine Offshore	1,50
Geothermal	0,90
Tidal	1,80
Hydropower	1
Biodegradable waste and biomass diverse from next point;	1,30
Biomasses and biogas from agricultural, zoo technical and forest residues;	1,30
Biomasses and biogas of previous point, feeding high-efficiency cogeneration plant reusing thermal energy in agricultural context	1,80
Landfill gases	0,8

Relatively to the first type of plants, the most common, incentives are sensibly cut compared to previous decrees, with an average yearly reduction of 16% of the initial value, while a comprehensive value will be provided by 2013, still to be discussed.

The second and the third solution presents a higher value of the incentive (e.g. 0.427 vs. 0.387 €/kWh for power plants higher than 20 MW), and also a less marked yearly reduction in incentive tariff, by about 4% until 2014.

2.3.3.1.4Energy Efficiency certificates

The Energy Efficiency Titles (“Titoli di efficienza energetica”, TEE), also named “White Certificates” are market-based instruments similar to the previously described system for renewable power production, promoting energy efficiency by using a system of quota exchanges between actors obliged to improve their energy efficiency (e.g. large power plants) and voluntary subjects which benefits for such incentives. The maximum duration of the incentive is variable, depending on intervention type. Three main types of certificates have been developed, referring to own reduction intervention (type I), natural gas reduction (type II) or other types of fuel (type III). The certificate, whose initial value had been established at 100 € per ton of equivalent oil saved, may also be calculated depending on bi-lateral agreements among the parts..

The modality for recognizing TEEs depends on the specific intervention, while the recent DM 5/09/2011 modified the system for calculating the methods for calculating the saved energy from cogeneration plants, which will be used later on in this work. For those plants, indeed, the amount of primary energy saved is calculated as:

$$\mathrm{RISP} = \frac{E_e}{\eta_{et}} + \frac{E_t}{\eta_t} - F_c \qquad (2.3)$$

Where E_e and E_c are the power and the heat saved due to the new installations (expressed in in MWh), η_{et} and η_c are fixed efficiency for power and heat production – representing the average national power and heat conversion efficiencies - and F_c is the amount of energy consumed by the fuel used by the plant, in MWh. The amount of TEEs (1 TEE = 1 toe) is calculated thanks to the relation:

$$TEE = 0.086 * RISP * K \qquad (2.4)$$

where k is a corrective factor depending on plant size (in terms of power capacity), shown on Table 2.9.

Table 2.9:Energy efficiency certificates: corrective factors for CHP plants

Size	K
P < 1 MW	1.4
1 < P < 10 MW	1.3
10 < P < 80 MW	1.2
80 < P < 100 MW	1.1
P > 100 MW	1

2.3.3.1.5Emission reduction certificates

Introduced at a communitarian level by the directive CE/87/2003, following the Kyoto Protocol, the GHG, Emission Trading Scheme (ETS) has been regulated in Italy by the d.lgs. n.273 of 12/11/2004. The mechanism is again similar to the one for renewable energy and energy efficiency, using a market base scheme, but, given the absence of a recognized market cost for carbon dioxide emissions, the “Emission Unit Allowances” (EUA) are only of interest of obliged subjects which has to limit their production activity due to the limits in emission quotas.

Other operating incentives: tax reduction

Eventually, tax reduction in Italy consists in reducing the amount of consumption taxes related to fossil fuel. In the civil field, such tax influence for more than 40% of total fuel costs, with variations depending on fuel type and consumption amount. In industrial field, however, such tax is much lower, negligible when compared to fuel price. Power production presents an even lower consumption tax, which is also negligible similarly to the industrial context. Such distinction is particularly relevant for CHP plants. The quota of energy designated for power production (calculated, for Natural Gas, as 0.25 m^3 for each kWh of power produced) presents the power consumption tax (thus negligible), while the residual quota is subjected to the normal application of the building assessed, civil or industrial. Given the previous considerations, such reduction is particularly relevant for the first case of civil buildings.

3

Methodology

3.1 The methodology

Chapter 1 and 2 provided a background of the research project related to both sustainable development, industrial ecology and decision support systems. On chapter 1, a path has been followed, showing how such concepts stems from and relates to each other, as outlined in the institutional and academic literature assessed. Particularly, the logics behind the concept of "Sustainable Development", has been analyzed, showing the link and the relevance of its triple viewpoint of techno-economic, environment and social aspects (Adams, 2006).

Such broad approach requires now a specific focus on the development of a Decision Support System aiming to help decision maker in choosing the *better* alternative among a range of many feasible solutions. The starting point for building the model has been identified on section 1.4, consisting on the general structure of a DSS and its three major steps of:

- Problem classification/definition ("Intelligence Phase");
- Alternative Generation/Evaluation ("Design Phase");
- Alternatives Negotiation/Selection and Action Determination ("Choice Phase").

Following this general structure, the methodology used throughout this work is reported on Figure 3.1.

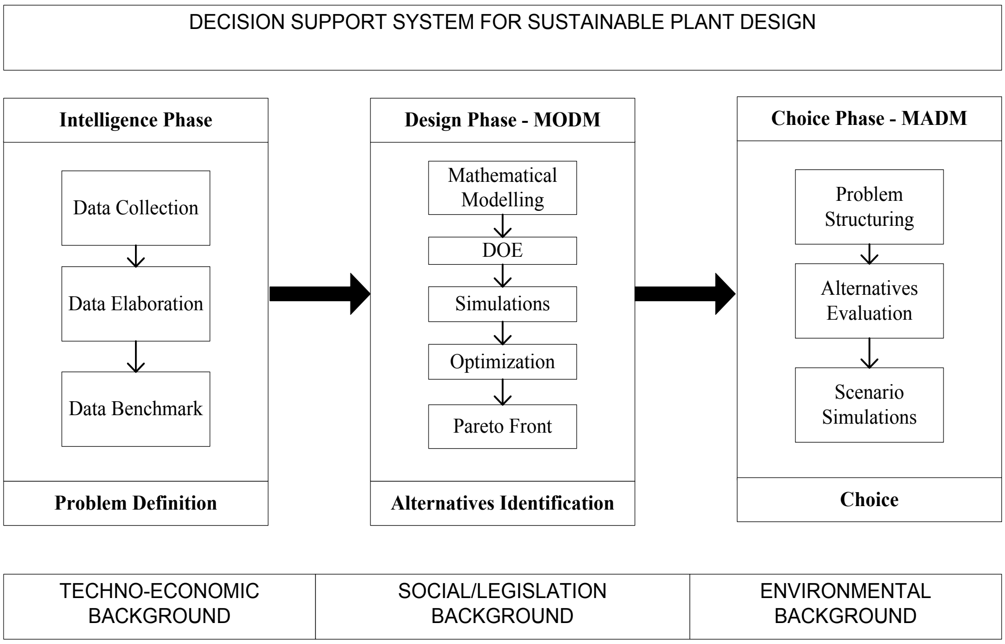


Figure 3.1: DSS for sustainable plant design, the methodology

As it's shown, the triple viewpoint, presented on chapter 2 represents the background of the DSS to be assessed, analyzing and providing the scope of the future case studies. Some of the tools used for each stage of the model will also be provided in this chapter.

Briefly looking at the model, the decision making process moves from a preliminary stage of data collection, elaboration and benchmark to a "creative" stage of alternative generation, which relies on mathematical multi-objective DSSs. Eventually, the choice among different alternatives is made by means of multi-attribute assessment, aiming to identify the best solution among a range of feasible alternatives. Before assessing each of the provided steps, a preliminary distinction of Multi-Attribute and Multi-Objective decision making – considered basilar for the following assessments – is provided.

3.1.1 Multi-Criteria, Multi-Objective and Multi-Attribute Decision Making

The major difference between these two methods can be traced in their very meaning. In fact, (Merriam-Webster, 2011) defines attribute as: *"an inherent characteristic"* and "*an object closely associated with or belonging to a specific person, thing, or office", w*hile the word objective means: *"something toward which effort is directed: an aim, goal or end of action"* From this very basilar analysis it emerges that, while attribute are used "ex-post" decision making - i.e. referring to a known situation - objectives are antecedent the decision making process. In other words, it can be said attributes are used to analyze something towards which the objectives have been chosen.

Considering the horizontal decision making process previously identified in figure 3.2, it can be stated that:

- Multi-Objective Decision Making provide support to the alternative generation stage – the 'design stage of Simon of previous paragraphs - allowing the decision maker to identify a range of alternatives;
- Multi-Attribute Decision Making supports the decision maker in the latter stage (the "Choice Phase") of selecting among a range of feasible alternatives.

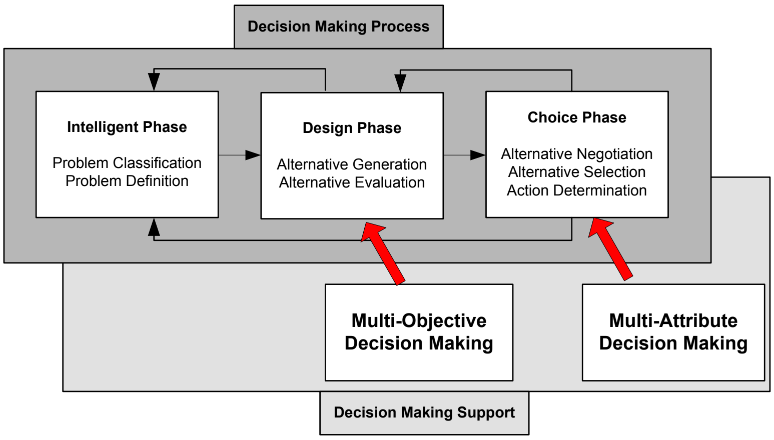


Figure 3.2: Decision Making process: Multi-Criteria and Multi-Objective analysis Adapted from (Burstein & Holsapple, 2008)

3.2 Section I: Intelligent phase – Data Assessment

The analytic stage consists in the preliminary step of data collection and evaluation aiming to provide to the following synthetic stages of a solid base to work on. The objectives of each step provided by the methodology on section 3.1 are shown on figure 3.3

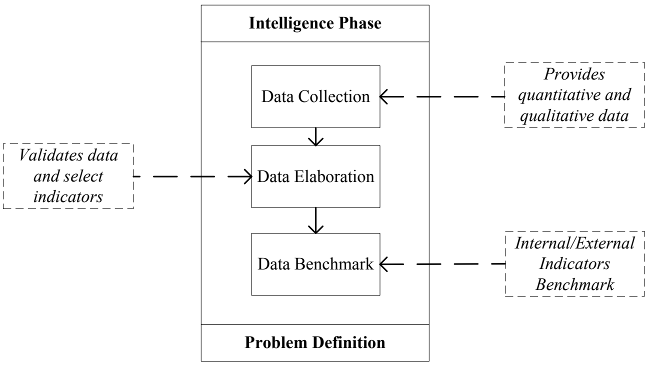


Figure 3.3: Intelligent Phase: sub-stages and objectives

A preliminary distinction between data, index and indicators, has to be firstly punctualized. As pointed out by (Jesinghaus, 1999) in using the DSPIR model for sustainability assessment in the EU, the so-called “Information Iceberg” has to be considered when assessing the information flow. The model distinguishes between data, indicator and indexes, as shown on Figure 3.4.

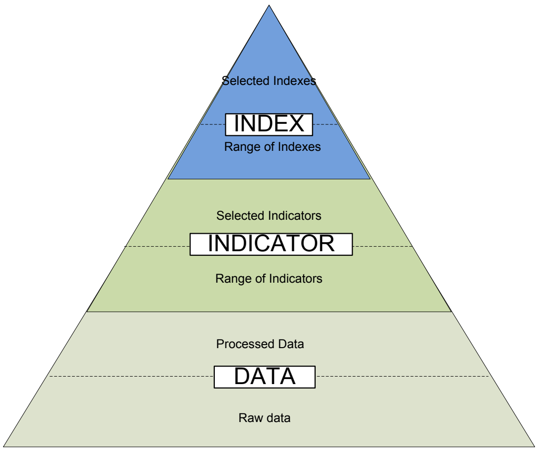


Figure 3.4: Information Iceberg. Source: Elaborated from (Jesinghaus, 1999)

Data are raw numbers, (e.g. Total electricity consuption: 1 GWh) which excludes any interpretation of the latter or any re-processing due to statistical adjusting or consistency analysis. A value like, for example, total energy consumption, in fact, while providing useful information on the “scale” of the variable to be analyzed, does not provide information whether the value is coherent, for example, with the best practices or similar industries. After data is validated (i.e. statistically considering only consistent values) combination of raw data allows to calculate *indicators* (e.g. Electricity consumption pro capita) whose significance allow multi-year monitoring and benchmark with similar realities. The passage from “data” to “indicator” is required, and it is commonly used in economic field (e.g. performance indexes such as ROI, ROE, Payback, ecc.) and will be a main feature assessed for the field study of this work. Indicators may also be further aggregated into indexes which would attempt to unify indicators with similar meaning, aggregating results in one single (or few) comprehensive quantitative values. Given this relevance of the “Intelligent Phase” for the future analysis, the latter has been be further split into three stages, accounting for three different moments of assessment:

- Data collection;
- Data elaboration;
- Data benchmark.

These stages will be assessed in the following sections.

3.2.1 Data collection

Site-specific assessment of the facility is referred as “Audit” (from the Latin word “audire”, meaning “methodical examination and review”, (Merriam-Webster, 2011), and it is required because the need of collecting reliable and coherent information, which are the basis of any future analysis to be done. Energy or Environmental Audit may be carried out in different modalities, such as ‘Walking Through’, ‘Extensive Audit’, ‘Specific Audit’ (Jayamaha, 2008), depending on the degree of specificity required by the assessment. “Walking through” audit, as the name suggests, are basilar inspection of the company’s premises, aiming to obtain a broad analysis of the structure and the problematic affecting the same; “Extensive Audit”, on the contrary, are long-term, comprehensive assessments of the structure which requires much more effort but allow to obtain a more detailed assessment of company’s priorities in the field of study; eventually, “Specific Audit” are tailored assessments of specific plants/machines (boilers, motors, ecc.) aiming to cope with a precise objective, usually following to one of the previous type of assessments.

Various modalities of data collection have been considered for this work, such as:

- Personnel interviews;
- Company’s inspection;
- Written questionnaire;
- Online questionnaire;
- Data-deriving from standard indicators;
- Access to central database.

Some of them are very straightforward (interviews, inspection), but require considerable time to be executed from both auditors and audited. Online questionnaire and database access, from the other side, presents evident advantages of rapidity and ease-of-use, but may not be applied to small/medium scale companies (which could not present the organizational structure to cope with such kind of surveys) while a central data base is usually present only in large applications or may not be consistent with current measurements. Standard indicators are useful for quick analyses of large amounts of sampled companies, when direct measurement would result time consuming when related to the project goal. The choice of the strategy for data collection is therefore very case-specific.

3.2.2 Data elaboration

As outlined by the Information Iceberg of paragraph 3.2, data collected from the previous step has to be elaborated in order to provide relevant outputs to the decision maker. In this model, the Indicators Approach has been used for provided for company’s assessment and benchmark, while impact assessment has been used for environmental indicator. Furthermore, statistics methodologies provide useful tools for data assessment, allowing identifying correlation among variables, thus simplifying the monitoring and planning processes.

3.2.2.1 Indicators Approach

The methods utilized for data assessment and elaboration is the derivation of *performance indicators* later to be benchmarked with industry standards or similar structures. Performance indicators (or Key Performance Indicators, as used in managerial fields) present many advantages which make them useful for multiple purposes. Some of the main features of an indicators, some of them taken from (Jesinghaus, 1999) are:

a) Simplicity: they are easy to calculate and provide essential information;
b) Monitorable: can be taken into consideration for different scales and scopes, timeframes, location;
c) Measurable: they provide a quantitative assessment of one or more variables.
d) indicators should support controversial political debates with non-controversial but relevant information;
e) complex political debates should be made more transparent by using a system of indicators (not just a “basket”);
f) highly aggregated indicators/indices are needed to communicate the most relevant information to those who have an interest in the debate, but do not want to be flooded with all the details;
g) value elements (weighting coefficients, valuation rules) must be clearly separated from objective elements (emissions of xyz);
h) indicators are not necessarily tools in themselves; in order to make them useful, they must be presented within their framework, and linked to standard socio-economic statistics;
i) the indicator system should provide enough detail to cover the political debates;
j) it should give continuity to the societal actors, in order to provide them with a good basis for the planning of e.g. investments or political instruments;
k) the indicator system should reflect the structure of the existing debates (and not try to introduce a “better” structure)

3.2.2.2 Emission Impact Assessment

Life Cycle Assessment represents one of the methodology to be used for evaluating the sustainability of products and, subsequentialy, a company. While keeping inventory of pollutants emissions represents a required step towards a sound environmental management, this stage only is not sufficient because it doesn’t allow keeping track of the effects of such pollutants discharges on the external environment. Life Cycle Impact Assessment (LCIA), as outlined in chapter 2.2.3, has been studied by several authors and has been included as a relevant step of the LCA methodology, integrated into the ISO 14000 standards.

Evaluating the environmental impact means assessing the effects of the particular use/production of an element. The environmental impact of an element *a* can be calculated as the total quantity (Q) of that element emitted during a specific time frame multiplied for the specific impact factor (IF) of a unit of that element, that is:

$$IA_a = Q_a \cdot IF_a \qquad (3.1)$$

It is clear that the importance of the value of the parameter IF considered for evaluating the impact of an element represents a key issue and the topic has been broadly studied in the academic literature. The methodology used for this report is the Eco-Indicator 99 as outlined in chapter 1, which calculates the global impact factor for the some relevant categories (Human Health, Ecosystem Damage, Climate Change, Ozone Depletion, Resource Depletion), some of them will be specifically addressed in the case studies.

3.2.3 Data benchmark

The intrinsic features of performance indicators allow comparison among similar contexts. At least four main categories of references, that is:

- External/Internal benchmark within the industry;
- Best available technologies and/or best practices;
- Theoretical process values;
- Regulatory limits.

Such broad base of confrontation has been used for comparing single company's performances in the case studies.

3.2.4 Statistical Tools for data elaboration and benchmark

Traditional statistical analysis also represents a powerful tool for data elaboration and benchmark. For the purpose of the study, the tool of correlation and regression analysis has been widely used for the case studies later presented. The indications provided in the following paragraph should not be considered nor complete or exhausting assessment of statistical methods for correlation analysis, but it provides some insight related to the meaning of the analysis which will be done in the case studies, which considered only correlations between two variables, thus excluding multi-variate interactions. Assessing the correlation between two variables might be done by assessing their *covariance*, defined as:

$$Cov(x,y)=\frac{\sum(x_i-\overline{x})(y_i-\overline{y})}{N} \qquad (3.2)$$

where $\overline{x}$ represents the average value of the distribution, x_i is the current value of the variable x, and N the amplitude of the sample. When cov(x,y) = 0, it means that the two variable are independent, while Cov = ±1 translates in direct or inverse relationship between the variables, at least in a two-variable problem. Correlation coefficient is useful for homogeneous variables (same unit of measurement), while for different scales, the *correlation coefficient* (*r*) is calculated by dividing the covariance by the variance of the two variables, thus "normalizing" the previous value.

$$r=\frac{\sum(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{(x_i-\overline{x})^2(y_i-\overline{y})^2}} \qquad (3.3)$$

Regression Analysis (RA), linear and non-linear, without entering much in detail about the related theory, is used to determine the best-fitted lines/curves to reported values. Ordinary Least Squares (OLS) is one of the most common methods for determining such curves, achieved by minimizing the Euclidian distance between reported and theoretical curve values. Determination coefficient (R^2), provides an indication of the goodness of the fitness, with values close to 1 meaning perfect fitness and values equal to 0 indicating null correlation. Regression proved to be useful due to:

- The correlation among data/indicators showed, for some cases, trends with good correlation ($R^2 > 0.8$), allowing to identify regression curves, which might prove useful for data forecasting;
- The indication of ±5% margin (the red dotted lines on figures) allowed evaluating values compared to the general trend, thus showing better or worse performances of some indicators.

3.3 Section II: Design phase: multi-objective decision aid

This second step represents the "creative" part of the work. Creative because its main aim is that of finding suitable solutions for the problem to be assessed. Logically, a "one-fit-all" solution would represent a clear error with respect to the broad assessment scope of the work, thus some limitations had to be applied for the application of stage two. In detail, the application of multi-objective modeling has been applied to one solution which, for many of the sample companies and buildings in the case studies later to be assessed, represented one of the most promising alternatives because of its intrinsic features of flexibility, efficiency and commercial development that is Combining Heating and Power (CHP) technologies. Furthermore, solar PV panels, due to the relevance and the advances of the technology, and the ever-increasing power costs experienced by the sampled companies, have been considered in the model. The objectives of the single steps provided for the Design Phase of the methodology are deepened on figure 3.5.

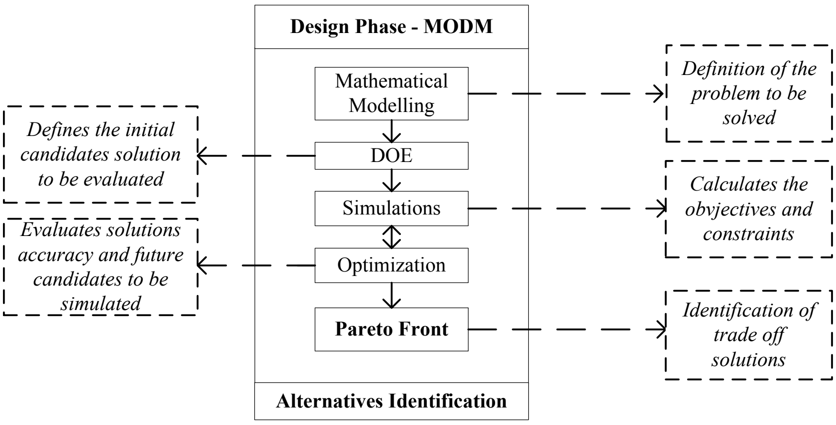


Figure 3.5: Design stage: substages and objectives

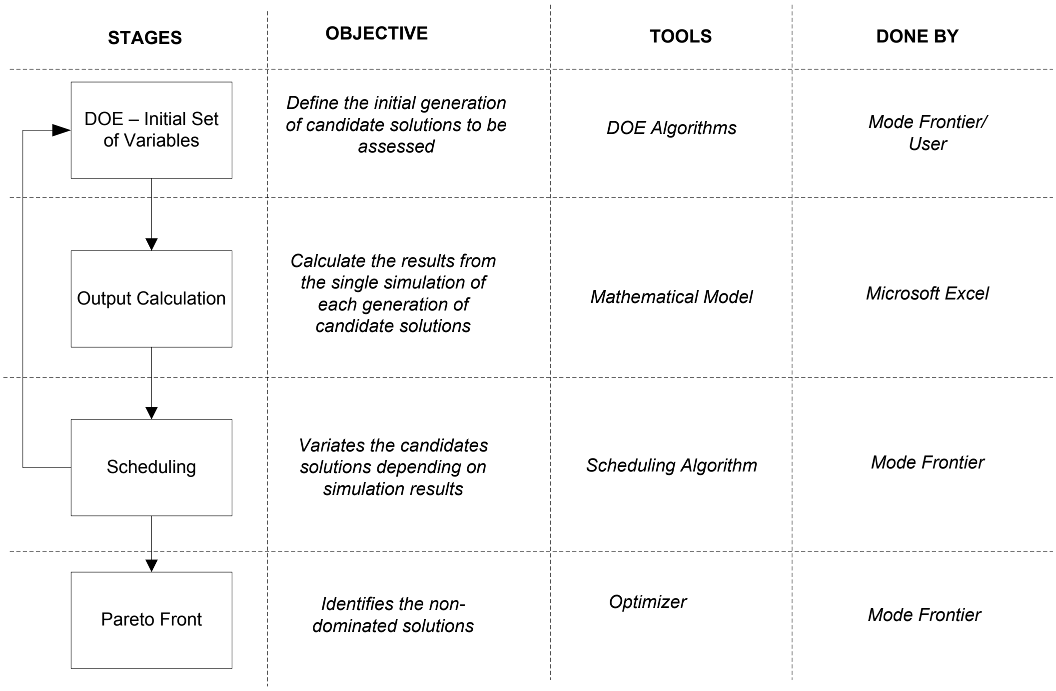
3.3.1 Multi-objective plant design

Multi-Objective analysis has been broadly used in components, product and plant design, while limited research has been considered when assessing environmental factors the process. (Vince, Marechal, Aoustin, & Bréant, 2008) assessed the design installation of a RO plant for desalinization including both economic and environmental criteria. Economics were related to capital and operations costs, while environmental impact, taking into account LCA, but ending up, given the relative absence of data regarding quantitative environmental assessment of water discharges, considering electricity production and water recovery rate as environmental criteria. (Harkin, Hoadley, & Hooper, 2011) used MO optimization for designing CO_2 capture systems retrofitted in coal power stations. Technical/Environmental criteria were used by the authors, which took into account the percentage of CO_2 captured (maximized) and the energy input to the process (minimized), evaluating results as a function of the input parameters. (Guillén-Gosálbez, 2011) applied MO optimization, discussing its validity when assessing multiple-objectives such as environmental ones, requiring high computational costs and introducing a mixed MILP-MO model then applied to heat exchanger designs and petro-chemical supply chains. Environmental impacts, considering a LCA approach, were considered, such as acidification, eutrophication, global warming and eco-toxicity. (Bernier, Maréchal, & Samson, 2010) used both thermo-economic and environmental objectives for Carbon Capture Plant design, integrating LCA (in terms of global warming potential) into the optimization model. (Mirzaesmaeeli, Elkamel, Douglas, Croiset, & Gup, 2010) treated environmental emission as a constraint to a MILP optimization of Ontario Power production, while optimization model proposed by (Rong & Lahdelma, 2005) included environmental emissions considered as externalities, i.e. as costs. (Dipama, Teyssedou, Aubé, & Lizon-A-Lugrin, 2010) applied evolutionary algorithms for power plant sizing considering technical (maximize exergy efficiency) and economic (minimizing total costs) criteria, identifying the Pareto-optimal solutions, while together considering a “Corridor Header Evolution Tracking”, which represents an innovative way for the searching protocol of the model. LP and MILP models for single objective optimization have been broadly used for energy plant sizing. Examples can be found by, (Lozano, Ramos, & Serra, 2010), (Bojić & Dragičević, 2002). An effective literature review of Distributed Energy Systems multi-objective planning has been provided by Alarcon-Rodriguez et alia (2010).

3.3.2 The optimization model

The optimization process proposed in the study operates as shown on Figure 3.6, consists in the following steps:

- The simulator (Microsoft Excel) receive a set of initial input variable’s values (Design of Experiment) from the optimization model;
- By calculating the desiderated output considering together variable and fixed/initial data, the simulator computes the desired output (objectives and constraints)
- Depending on the optimizer, constraints are verified and feasible solutions are assessed depending on the objective functions, while solution set is eventually kept, modified or discarded;
- The optimizer stops after a pre-determined number of iterations and non-dominated solutions are thus identified.



STAGES	OBJECTIVE	TOOLS	DONE BY
DOE – Initial Set of Variables	*Define the initial generation of candidate solutions to be assessed*	*DOE Algorithms*	*Mode Frontier/ User*
Output Calculation	*Calculate the results from the single simulation of each generation of candidate solutions*	*Mathematical Model*	*Microsoft Excel*
Scheduling	*Variates the candidates solutions depending on simulation results*	*Scheduling Algorithm*	*Mode Frontier*
Pareto Front	*Identifies the non-dominated solutions*	*Optimizer*	*Mode Frontier*

Figure 3.6: Logic Model of the Optimization Process

The model here proposed presents the following peculiar features:

- The model include a multi-objective optimization of a CHP plant design considering both economic and environmental objective function *separately*, avoiding processes such as externalization;

- The optimization model is run on a two-software base, using the flexibility of Microsoft Excel^{TM} in data insert and calculation, while exploiting multi-objective optimization algorithms provided by the Esteco ModeFrontier^{TM} package for searching the Pareto front;

- The choice among cogenerating technologies, resembling the decision making process in real scenarios, is made on a *discrete* level, that is considering current plant size (and related features such efficiencies, etc.) available on a commercial level;

- The main technologies used for CHP considered in the study are natural gas-fuelled internal combustion engines, liquid-fuelled internal combustion engines (diesel and bio-oil), natural gas turbines, natural gas micro-turbines, natural gas fuel cells; PV technologies has been split in monocrystalline and poly-crystalline technologies.

- The optimization process considers site-specific heat and power loads on a monthly basis, together with data available on radiation level (direct plus diffused) available from meteorological databases such as (PVGIS, 2011); operating hours (e.g. number of daily shifts) have also been considered for a more specific site assessment in manufacturing companies.

A detailed assessment of input data, variables, constraints and objective functions will be considered in the following chapters. The mathematical model used in the simulation process will also be assessed.

3.3.3 Site-specific Input data

The model requires some basic information regarding the facility studied. The information required by the model is:

- Type of fuel used for heat production;
- Heat (HL_{mo}) and power (PL_{mo}) loads on monthly basis;
- Local irradiation (kWh/m^2) on the specific latitude of the studied facility (IRR_{mo});
- Daily operating hours (H_d) and weekly worked days (D_w);
- Available facility area on plant (APA)

3.3.4 Fixed Input Data

In order to compute the economic, technical and the environmental factor utilized by the model, some variable had to be fixed depending on the specific case. Specifically, the following values have been taken as references, i.e.

- Fuel price (FP_c) and Power Price (PP): when possible, current fuel costs at the specific location were taken as reference. Alternatively, market-based fuel costs were utilized;
- Plant specific investment costs (IC_t): economic analysis of current plant costs was computed from both local market surveys and literature values (as reported on chapter 2). The values taken as a reference for the technologies, including the notations which will be used later in the chapter, and as it will be investigated in next sections, are shown on Table 3.1.

Table 3.1: CHP technologies, capital costs and regression curves

Technology	**Specific Investment costs [y] [€/kW]**	**Regression Curve [x = Plant Power, Pe]**
T1) Gas Engines T2) Diesel Engines T3) Bio-Oil Engines	2000/3000 (< 60 kW_e) , 1000/ 2000 (60 kW to 1 MW_e) 700 – 1000 (> 1MW_e)	$y = 5745x^{-1.191}$
T4) Gas Turbines	1000 – 1500	$y = 6463.8x^{-0.223}$
T5) Micro-Turbines	2000 – 3000	$y = -1124\ln(x) + 7816$
T6) Fuel Cells	3000 – 4000	$y = -322.2\ln(x) + 4716$
T7) Solar PV – Monocrystalline	3000	$y = 3000$
T8) Solar PV – Polycrystalline	3300	$y = 3300$

- Maintenance costs, as related in chapter 2, were also computed from both market analysis and literature analysis. General values together with the regression curves computed and used by the model, are shown on table 3.2.

Table 3.2: CHP technologies, maintenance costs and regression curves

Technology	**Maintenance Costs [y] [c€/kWh]**	**Regression Curve [x = Plant Power, Pe]**
Gas Engines Diesel Engines Bio-Oil Engines	2-3.5 (< 1MW), 1.5 (> 1MW)	$y = -0.435 \cdot \ln(x) + 4.5012$
Gas Turbines	0.5 – 0.	$y = -0.098 \cdot \ln(x) + 1.4$
Micro-Turbines	1.4 – 2.8	$y = 6463.8x^{-0.223}$
Fuel Cells	3 – 1.5	$y = -322.2\ln(x) + 4716$
Solar PV – Monocrystalline	1.3 % of plant investment, including insurance costs, which represents an average expenditure of 3 / 3.5 c€/kWh	
Solar PV – Polycrystalline		

- Plant reliability (R_t), has been reported on chapter 2, showing the values on table 3.3.

Table 3.3: CHP Technologies reliability

	Reliability
ICE	0.91 (< 1 MW_e), 0.95 (> 1MW_e)
Gas Micro-turbine	0.95
Gas Turbines	0.95
Fuel Cells	0.96

- Average losses of PV plant (R_{PV}), depending on distribution, transmission and inverter losses, have been accounted for 15% of converted power at the cell.
- Plant specific emission factors for most relevant pollutants (ER_p): emissions of NOx, SOx, CO, NMVOC and PM were considered. Specific emission factors have been reported on section 2.1.5 for each CHP technology.
- Emission factors of traditional boilers (EF_p), as reported in AP-42 standards (table 3.4), were considered for calculating the amount of saved emissions by the solution to be assessed. Emission factors used in the study are taken from the AP-42 US-standards

Table 3.4: Emission factors from traditional boilers

Fuel Used		**UM**	**NOX**	**CO**	**PM**	**SO2**	**NMVOC**
Natural Gas	kg/UM	m3	0.0016	0.0013	0.0001	0.0000	0.0001
Diesel	kg/UM	l	0.0024	0.0006	0.0002	0.0001	0.0000
BTZ Oil	kg/UM	kg	0.0073	0.0007	0.0013	0.0209	0.0000
LPG	kg/UM	l	0.0018	0.0010	0.0001	0.0000	0.0001

Similarly, avoided impact from current power production system, has been calculated by using EU IPCC emission factors (which however refers to the US EPA - AP 42 standards), by considering the emission factors for each single fuel, the current national fuel mix, the percentage of power produced by renewable energy and the current fuel mix. Emission factors, expressed as a gram of pollutant per kWh produced, are reported on table 3.5.

Table 3.5: Emission factors from power production

	g/kWh out
NOx	0.91
PM	0.04
NMVOC	0.01
SOx	1.38
CO	0.33

- Current incentive system: related the specific locations of the research projects, the incentives specific to the facility analyzed were taken into consideration. In Italy, incentives on power produced from renewable energy, I_{CV} – thus used for bio-oil ICEs - are currently (October 2010) at 0.07 €/kWh, while feed-in tariffs for PV plants (I_{PV}) depending on plant size and considering only roof-integrated solutions, is reported on table 3.6.

Table 3.6: Feed-in tariffs for PV power production

Ranges of Installed peak power [kW_p]	**Feed-in Tariffs [€/kWh] - I_{pv}**
1 – 3	0.274
3 – 20	0.247
20 – 200	0.233
200 – 100	0.224
1000 – 5000	0.182
> 5000	0.171

Referring to the energy efficiency incentives, recent Italian decree on cogeneration incentives, determined the amounts of saved energy to be used for calculating the total amount of the economic incentives, together with the current value of the "certificati bianchi" (energy efficiency certificates) is 99 €/toe. However, such incentive cannot be cumulated with the previous form of incentive ("green certificates") and with the consumption tax reduction on fossil fuel when used for power production (see 2.3) which was also included in the model. Energy efficiency certificates have been therefore excluded by the analysis.

- Impact factors of pollutants: an impact factor of the previously computed pollutants, as defined in the Life Cycle Impact Assessment Stage (see paragraph 2.2.3), has been computed in order to unify the impact value of the various emissions. Impact factors which have been used in this study are expressed on Table 3.7 and are related only to the category Human Health impact, and are expressed in terms of DALY/kg, as explained on section 3.2.2.2.

Table 3.7: Human Health Impact factor for Macro-Toxicants

	DALY/kg
NOx	0.006
CO	0.000
PM10	0.024
SOx	0.004
NMVOC	0.0001

Fixed parameters variations have also to be taken into consideration while considering plant economic and financial assessment over multiple years. The following parameters have been considered:

- Variation in energy costs: power and fossil fuel prices are rapidly ascending, with a variable but crescent trend. For example, values from the Italian national statistics (ISTAT) show an average increase of about 6% in power and fossil fuel prices.

- Variation in national incentives: only fixed variations have been considered, together with the duration of the incentives, has been considered. Planned reduction in feed-in tariffs for PV plants accounts for about 16% for the first 5 years, then stabilizing for the remaining duration of the incentive, i.e. 15 years.

- Variation in national incentives such as green certificates for other renewable energy production and the white certificates for energy efficiency, together with the prices of bio-oil, has not been varied in the modeling phase but in the sensitivity stage. The volatility of such values is so high that it wasn't considered right to assume a fixed variations throughout the years. However, the duration of such incentives is limited to 15 years (Green Energy Certificates) and 10 years (Energy Efficiency Certificates).

3.3.5 Model Variables

The optimization model has to decide which plants optimize the objective functions later to be described. The total number of variables is 7, each one with specific ranges and steps of variation. The main variable of the decision making process is:

- Technology type (T_t), varying among the specified technologies on previous paragraph; plant model (M_n), varying among the commercially available models for the technology assessed, which varies the size (electrical, P_e and P_t and related efficiencies), for a total of 7 variables.
- Number of plant model per type (N_{mt}), defining the redundancy of the system, varying, for CHP technologies, between 0 (no plant installed) and 4 (step: 1). Five variables are thus considered..

  The number of this variable is thus 12 (number of months) per 5 (number of CHP technologies), equal to 60.

- Surface area (S_{mc}, S_{pc}) percentage dedicated to PV technologies (monocrystalline *mc* and polycrystalline *pc*, two variables), varying between 0 and 1 (step 0.05);

- Minimum Percentage of Heat and Power (MIN_H, MIN_P, two variables) loads to be satisfied, i.e. the amounts of energy which has to be provided to the system for maximizing the objective functions.

3.3.6 The mathematical model

A mathematical model is now reported for synthesizing the computations made by the Excel spreadsheet. The notations presented on the previous section will be used.

3.3.6.1.1Energy Production and Fuel Consumption

Firstly, the power produced (E_{el}^{chp}) by the cogeneration plants (t = 1 to 5) can be calculated as:

$$E_{el}^{chp} = \sum_{t=1}^{5} \sum_{m=1}^{12} P_{el}^{t} \cdot N_t \cdot [h_d \cdot \frac{d_w}{7} \cdot GG_m \cdot R_t] \qquad (3.4)$$

Of equation 3.4 Ptel (the size of the plant of the selected technology), Nt (the number of similar plants of the technology t) are the variables which the model will have to optimize, while h_d (daily hours in which the facility operates), d_w (number of days in the week in which the plant is working), GG_m (number of days in the month considered) and R_t (reliability of plant t) are fixed values. To ease future reading, the factor between the square brackets will be named EH (equivalent hours). Equation 3.4 becomes:

$$E_{el}^{chp} = \sum_{t=1}^{5} \sum_{m=1}^{12} P_{t}^{el} \cdot N_t \cdot EH_{m,t} \qquad (3.5)$$

Similarly heat produced by CHP plants, which corresponds to the total heat produced by the system (E_{h}^{chp}) will be calculated as:

$$E_h = E_{h}^{chp} = \sum_{t=1}^{5} \sum_{m=1}^{12} P_{t}^{th} \cdot N_t \cdot EH_{m,t} \qquad (3.6)$$

Power produced by PV plant is calculated as:

$$E_{el}^{PV} = \sum_{t=5}^{6} \sum_{m=1}^{12} IRR_m \cdot S_t \cdot \eta_t \cdot L_{PV} \cdot APA \qquad (3.7)$$

Where L_{pv} are the losses of PV plants (inverter, transmission, heat losses), accounting for about 15% of total converted input, and APA (Available Plant Area) is the available surface of the considered location and IRR_m is the average monthly radiation of selected facility.

Therefore total power produced by the system is equal to

$$E_{el} = E_{el}^{chp} + E_{el}^{PV} \qquad (3.8)$$

Yearly Fuel Consumption (FC_t) of the CHP technologies has been calculated considering the power installed, the electrical efficiency η_{el} (thermal efficiency could have been used either) and the equivalent hours, as:

$$FC_t = \sum_{m=1}^{12} k \cdot \frac{P_{t}^{el}}{\eta_{el} \cdot LHV_t} \cdot N_t \cdot EH_{t,m} \qquad (3.9)$$

Where LHV is the lower heating value of the fuel associated to the technology *t* and k is the conversion unit depending on the unit of measurements in use. FC_6 and FC_7 – fuel consumption of PV plants – are equal to 0.

3.3.6.1.2Cost analysis

Fixed and variable costs are included in this category. On the first category, traditional investment costs are calculated depends on specific investment costs ($C^{inv,sp}$ in €/kW) which in turns relates to plant size:

$$C^{inv,sp} = f(_{Pel}) \qquad (3.10)$$

Having implemented the regression curve on the specific cost calculator in the Excel Spreadsheet, total cost costs (TCC) are calculated as:

$$TCC = \sum_{t=1}^{7} P_{el,t} \cdot C_t^{inv} \quad (3.11)$$

Among variable costs, the following items have been considered:

- Fuel costs;
- Maintenance costs;
- Power Integration Costs;
- Heat Integration Costs;
- Heat dissipation costs.

Fuel costs are dependent on fuel consumption and specific fuel costs associated to the technology being considered, and are calculated as:

$$C^{fuel} = \sum_{t=1}^{7} FC_t \cdot C_t^F \qquad (3.12)$$

Maintenance costs (C^m) of CHP technologies are (see chapter 2) expressed as €/kWh produced (C_t^m, specific maintenance costs, also depending on plant size), including a full-service maintenance contract. Therefore we have:

$$C^{m,chp} = \sum_{t=1}^{5} E_{el,t}^{chp} \cdot C_t^m \qquad (3.13)$$

while, as noted on section 2.1.4.3, maintenance and insurance costs of PV plant are expressed as a percentage of total investment costs, as:

$$C^{m,pv} = \sum_{t=6}^{7} C_t^{inv} \cdot 0.013 \qquad (3.14)$$

Total maintenance costs, therefore are calculated as:

$$C^m = C^{m,pv} + C^{m,chp} \quad (3.15)$$

Power integration costs, depends on the difference on monthly basis the current load requirements and between total power produced, (when this difference assumes positive values) and the current power costs (PP, in €/kWh), that is:

$$if\,(E_{el,m}^{req}-E_{el,m})>0,C_{el,m}^{\text{int}}=(E_{el,m}^{req}-E_{el,m})\cdot PP \qquad (3.16)$$

$$C_{el}^{\text{int}}=\sum_{m=1}^{12}C_{el,m}^{\text{int}} \qquad (3.17)$$

Similarly, heat integration costs are calculated as:

$$if\,(E_{h,m}^{req}-E_{h,m})>0,C_{h,m}^{\text{int}}=(E_{h,m}^{req}-E_{h,m})\cdot FP \qquad (3.18)$$

$$C_{h}^{\text{int}}=\sum_{m=1}^{12}C_{h,m}^{\text{int}} \qquad (3.19)$$

Where FP is the current specific price of the specific fuel used by the facility, adjusted to be aligned with the unit of measurement of the heat energy previously calculated.

Adversely, excessive heat has to be eliminated. Excessive heat costs, which are basically power costs for water pumping or refrigeration, has also been computed by Lozano et alia (2005) and amount at an average yearly price of 13 €/MWh_t of heat.

$$if\,(E_{h,m}^{req}-E_{h,m})<0,C_{h,m}^{exc}=(E_{h,m}-E_{h,m}^{req})\cdot C_{exc} \qquad (3.20)$$

$$C_{h}^{exc}=\sum_{m=1}^{12}C_{h,m}^{exc} \qquad (3.21)$$

Total annual costs (TAC), therefore, are calculated as:

$$TAC=C^{fuel}+C^{m}+C_{el}^{\text{int}}+C_{h}^{\text{int}}+C_{h}^{exc} \qquad (3.22)$$

3.3.6.1.3Revenues analysis

Positive cash flows from the system are to be found in the following items:

- Exceeding power sold to the grid;
- Avoided costs of power production;
- Avoided costs of heat production;
- Revenues from national incentives

Exceeding power sold to the grid is calculated similarly to equation (3.20), only when the difference between current load and power production is negative:

$$if\,(E_{el,m}^{req}-E_{el,m})<0,R_{el,m}^{exc}=(E_{el,m}-E_{el,m}^{req})\cdot PP_{grid} \qquad (3.23)$$

$$R_{el}^{exc} = \sum_{m=1}^{12} R_{el,m}^{exc} \qquad (3.24)$$

Power price sold to the grid is generally fixed and inferior to the current price of the power bought. Current Italian price of the energy sold to the grid is, for example, 80 €/MWh.

Avoided costs of power production are calculated as:

$$if\,(E_{el,m}^{req} - E_{el,m}) \geq 0, R_{el,m}^{av} = R_{el,m}^{req} \cdot PP \qquad (3.25)$$

$$R_{el}^{av} = \sum_{m=1}^{12} R_{el,m}^{av} \qquad (3.26)$$

While avoided costs for heat production are:

$$if\,(E_{h,m}^{req} - E_{h,m}) \geq 0, R_{h,m}^{av} = E_{h,m}^{req} \cdot HP \qquad (3.27)$$

$$if\,(E_{h,m}^{req} - E_{h,m}) < 0, R_{h,m}^{av} = E_{h,m} \cdot HP \qquad (3.28)$$

$$R_{h}^{av} = \sum_{m=1}^{12} R_{h,m}^{av} \qquad (3.29)$$

Eventually, revenues from national incentives are calculated for the following items:

- I_{bo}: Renewable energy production from bio-oil CHP plant (t = 3)
- I_{pv}: Renewable power production from PV plants (t =6, 7);
- I_{EE}: Energy efficiency certificated from CHP plants (t = 1-5)

where, considering the notations on previous paragraphs:

$$I_{bo} = (\sum_{m=1}^{12} P_{t=3}^{el} \cdot N_{t=3} \cdot EH_{m,t=3}) \cdot I_{CV} \qquad (3.30)$$

$$I_{PV} = E_{PV}^{el} \cdot I_{PV} \qquad (3.31)$$

$$I_{EE} = (\frac{\overline{E_{sav}^{el}}}{\eta_{es}} + \frac{\overline{E_{sav}^{h}}}{\eta_{ts}} - F_c) \cdot 0.086 \cdot k \cdot I_{CB} \qquad (3.32)$$

where $\overline{E_{sav}^{el}}$ and $\overline{E_{sav}^{h}}$ are the effectively saved energy of the system, not considering PV plants which are not included in this incentive, but only considering actual energy savings from the current situation. Total revenues from incentives are thus calculated as:

$$I = I_{bo} + I_{PV} + I_{EE} \qquad (3.33)$$

Synthesizing, total annual revenues (TAR) are calculated as:

$$TAR = R_{el}^{exc} + R_{el}^{av} + R_{h}^{av} + I \qquad (3.34)$$

Annual cash flow, for each year *y*, is simply calculated as:

$$\mathrm{ACF}_y = \mathrm{TAR}_y - \mathrm{TAC}_y \qquad (3.35)$$

3.3.6.1.4Cost and revenues variations

Costs and revenues are subjected to fixed variations due to the factors identified on previous paragraphs, therefore the values previously computed has to be computed on a yearly basis, also considering the depreciation factor and possible limitation in the duration of the cash flow (e.g. incentives). Variation factors considered by the models, associated with the values previously calculated, are reported on table 3.8. Modified annual cash flows are calculated for each year of the investment duration, supposed to be 20 years, as:

$$\overline{ACF}_y = \overline{TAR}_y - \overline{TAC}_y \qquad (3.36)$$

Net present value, sum of the modified cash flows, is therefore calculated as:

$$NPV = \sum_{y=0}^{20} \overline{ACF}_y - I_o \qquad (3.37)$$

Table 3.8: Cost and revenues variations considered in the model

Factor	**Value per year**	**Affected variable**
Variation in power prices	6%	R_{el}^{av} Revenues from avoided power costs C_{el}^{int} Costs of integrated power C_{h}^{exc} Costs of exceeding heat disposal
Variation in fossil fuel prices	6%	R_{h}^{av} Revenues from avoided heat costs C_{h}^{int} Costs of integrated heat C^{fuel} Fuel Costs
Variation of PV module efficiency	-0.7%	I_{PV} Revenues from PV incentives
Variation of feed-in tarifs for PV	-16% (5 years)	I_{PV} Revenues from PV incentives
Duration of green power certificates	15	I_{bo} Revenues from power production of bio-oil plant
Duration of energy efficiency certificates	10	I_{EE} Revenues from energy efficiency certificates
Discount factor	5%	ACF: annual cash flows

3.3.6.1.5 Environmental impact analysis

Environmental impact has been calculated as a sum of the emissions emitted by each technology during its operating period, which has to be subtracted of the emissions avoided by heat and power production.

Emissions rates (ER) from the current system has been divided per pollutant *p* (NO_x, CO, SO_2, NMVOC, PM) emitted from each technology *t*, and then unified by the impact factor (IF) expressed in DALY/kg, as presented on section 3.3.4. Considering the unit of measurement of emission rates (grams per unit of fuel, the latter variable depending on fuel type), current environmental impact (CEI) is thus calculated as:

$$CEI = \sum_{p=1}^{5} \sum_{t=1}^{7} FC_t \cdot ER_{t,p} \cdot IF_p \qquad (3.38)$$

Avoided impact from power production has been calculated for all the electricity output of the system, considering the emission factors of the power production mix of the country, as reported on paragraph 3.3.4.

$$AEI_{el} = \sum_{p=1}^{5} EL \cdot ER_p^{el} \cdot IF_p \qquad (3.39)$$

while avoided impact from heat production depends only on effectively exploited heat from the CHP system. This value is calculated as

$$if\,(E_{h,m}^{req} - E_{h,m}) \geq 0, AEI_h = \sum_{p=1}^{5} E_{h,m}^{req} \cdot ER_p^h \cdot IF_p \qquad (3.40)$$

$$if\,(E_{h,m}^{req} - E_{h,m}) < 0, AEI_h = \sum_{p=1}^{5} E_{h,m} \cdot ER_p^h \cdot IF_p \qquad (3.41)$$

$$R_h^{av} = \sum_{m=1}^{12} R_{h,m}^{av} \qquad (3.42)$$

Total Environmental Impact Reduction (TEIR) is therefore calculated as:

$$\text{TEIR} = \text{AEI}_{el} - \text{AEI}_h - \text{CEI} \qquad (3.43)$$

3.3.6.1.6 Objective functions and constraints

The optimization model evaluates different combinations of plants and operating conditions in order to:

- Maximize total value of the investment, *Max(NPV)*
- Maximize total environmental impact reduction, *Max(TEIR)*

Constraints which have been applied to the system mainly refer to both effective constraints of the model and control values dictated by the model construction such as:

- Sum of the percentages of the available plant area allocated to monocrystalline and polycrystalline PV plants, whose maximum value is equal to one;

$$S_6 + S_7 = 1 \qquad (3.44)$$

- Control of the minimum amount of energy requirements to be produced by the system, variable but constrained on the value of variables;

$$E^{el} > MIN\_P \cdot E^{el,req} \qquad (3.45)$$

$$E^{h} > MIN\_H \cdot E^{h,req} \qquad (3.46)$$

A constraint has also been considered for limiting excessive over sizing of the plant (avoiding waste heat to be disposed of), following the Italian incentives for high-efficiency cogeneration, the limits have been written as:

$$\frac{E^h}{E^h + E^e} > LT_{\min} \qquad (3.47)$$

Which states the amount of heat energy *exploited* d by the CHP plant over the total exploited energy has to be superior to a fixed value (0.33).

3.3.6.1.7Mathematical model, a synthesis

Synthesizing, the optimization model is therefore calculated by optimizing the following objective functions:

$$Max(NPV) \qquad (3.48)$$

$$Max(TEIR) \qquad (3.49)$$

Where NPV represents the actualized sum of the cash flows (ACF), actualized and considered throughout the whole duration of the investment ($\overline{ACF_y}$), consisting in actualized revenues (TAR) and costs (TAC), in turn depending on revenues from (sold exceeding and avoided purchasing of electricity, avoided purchasing of heat and incentives) and variable costs (fuel consumption, maintenance, heat and power integration and excessive heat disposal).

$$NPV = \sum_{y=0}^{15} \overline{ACF}_y - I_o = \sum_{y=0}^{15} \left(\overline{TAR}_y - \overline{TAC}_y \right) = \sum_y \sum_m \sum_t \left(\overline{R}_{el}^{exc} + \overline{R}_{el}^{av} + \overline{R}_h^{av} + \overline{I} \right)_{y,m,t} - \sum_y \sum_m \sum_t \left(C^{fuel} + C^m + C_{el}^{\text{int}} + C_h^{\text{int}} + C_h^{exc} \right)_{y,m,t} \quad (3.50)$$

Total environmental impact reduction (TEIR), is calculated as a sum of avoided emissions electricity, avoided emissions from heat production and environmental impact of the system to be evaluated.

$$TEIR = AEI_e + AEI_e - CEI = \sum_{p=1}^{5} EL \cdot ER_p^{el} \cdot IF_p + \sum_{p=1}^{5} E_{h,m}^{req} \cdot ER_p^h \cdot IF_p - \sum_{p=1}^{5} \sum_{t=1}^{7} FC_t \cdot ER_{t,p} \cdot IF_p \quad (3.51)$$

Subjected to conditions in order to promote:

- Correct plant sizing (avoiding excessive heat wasted);
- Satisfying a percentage of company’s heating and power needs;
- Respect site-specific limits (e.g. available roof area).

3.3.7 Design of Experiments – DOE

The identification of the initial set of candidates solutions (Design of Experiments, DOE), i.e. the combination of variables to be simulated by Microsoft Excel, represents a major stage in the whole optimization process. Among the advantage of a consistent DOE, the rapidity of the optimization process for rapidly converging to optimal solutions, is probably of the most relevant.

The design space is defined by the number of variables multiplied by the number of variables ‘levels (i.e. the allowed values for each variables). Given a problem with 5 variables, each one with 3 possible levels, the maximum number of design combination is $5^3 = 125$ designs. Obviously, increasing the number of variables and levels, increases the complexity of the problem. Over the hypercube defined as the polyhedron with a number of dimensions equal to the number of variables (e.g. 3 variables with equal level size is represented by a cube), the initial design space can be selected in various ways.

The software used for the optimization process (Esteco Mode Frontier 7.0) allows the following DOEs algorithm, whose operating principles are briefly assessed:

- User defined sequence: an initial ASCII file can be directly inserted into the design space, useful when some feasible solutions are already known and the optimizer can start from an-already feasible solution;

- Random DOE: the design space is filled randomly after setting up a generator seed;

- Sobol sequence: similar to the previous DOE, but allowing a more uniform distribution of the randomly generated points of the design space;

- Constraint Satisfaction Problem (CSP), is used for highly constrained designs and optimization algorithms requiring an initial feasible solution to operate. The algorithm used the “record-to-record travel” operation, moving from a feasible solution to a “not much worse” solution, where this parameter is set up initially by the user, by setting the “allowed deviation” (AD). Low AD rapidly converge but may provide local optima, while high values requires larger computing;

- Latin Hypercube/Montecarlo, which is a random DOE over statistical distributions (Montecarlo), while Latin Hypercube divide the distribution over homogeneous intervals to improve the spread of the candidates;

- Full Factorial DOE: after having defined the variable levels (the number of possible values, *l*) for each variable *v*, the total number of combination (v^l) is calculated. Useful for problems with low number of variables, because of the large computing required for assessing the whole design space;

- Reduced Factorial DOE: similar to the previous methodology, but with a maximum of 2 levels allowed for each variable, permitting the possibility of considering variable distances from the extreme points of each variable;

- Cubic Face Centered DOE, which is a 2-level full factorial DOE , but also considering mid points each variable combination (the hypercube) of the design space;

- Box-Behnken DOE, which considers the centre of the hypercube constituted by the design space, plus the midpoints of each variable;

The software also allows other DOE algorhytms such as the Latin Square Method (LSM), Taguchi method, Plackett-Burman, D-Optimal and Cross Validation DOE. The choice among the different types of DOE will be assessed in the specific application of the MO optimizations.

3.3.8 Scheduling: Optimization processing

Having fixed the initial set of solution for which the output values have been assessed, the optimizer has to decide *how* to move from a set of candidates to the next one, in order to identify best-performing candidates. This process, known as scheduling, depends on many variables such as:

- Variable type: continuous vs. discrete,
- Search operators: mutation/selection/crossover (see paragraph 1.4.2.1);
- Relation among generations (keeping best solutions, i.e. elitism, or changing completely the generation set)
- Computing capabilities: varying the number of contemporary assessed variables;

Some mechanisms for multi-objective search among candidates solutions have been reviewed on section 1.4.2.1, while the available schedulers on the optimization software used in this work are now briefly assessed:

- MACK (Multi-Variate Adaptive Cross validating Kringing), which is used when exploring whole the design space is more important than the otpima identification itself. This scheduler, therefore, is an evolution of the DOE, selecting new candidates by interpolating previous generations and selecting only the less accurate (by means of accuracy coefficients defined by Kringing), in order to increase diversity to the solution candidates;

- Lipschitz sampling, generating design in most complex region of the design space, where the complexity is determined by the value of the Lipschitz constant. Future candidates are trying to maximize distance from already-evaluated points;

- Multi-Objective Genetic Algorithms (MOGA) II, which is a proprietary algorithms which, starting from a set of candidates solutions ("parents") evolves in more candidates (the "children"), by using the following search operators:

    - Crossover: recombination of parents);

    - Selection: maintain designs;

    - Mutation; changing only limited designs

  The methodology allows elitisms (best solution of each objective are preserved from one generation to the next one) and treats constraints in order to ensure best constraints satisfaction among generations, done by adding an objective equal to the number of violated constraints to be minimized;

- Adaptive Range MOGA (ARMOGA), which is a scheduler similar to the previous one, with the possibility to change the design accordingly to the solutions calculated on the previous generations, by means of defining a "*range adaptation*" parameter, which varies the number of candidates to be preserved/changed each generation, in turn affecting convergence time and solution diversity;

- Non Dominated Sorting Genetic Algorithm (NSGA-II). This algorithm search new candidates depending on the level of "non-domination" of each solution. This algorithm required high computing (especially for large population sizes), but it includes elitism and can provide high diversity among the candidates solutions. NSGA-II shares with MOGA the search operators and the application of penalties are included for treating constraints violation.

- Multi-Objective Simulated Annealing (MOSA): the scheduler alternatively works in "hot" and "cold" phases, where the designs are perturbed by a minimum perturbation ("cold" phase) or by altered (increased) perturbations ("hot" phase), decided by user settings.

- Multi-Objective Game Theory (MOGT), which is a methodology taken from the application of Game Theory from social and economic science, where each "player" tries to maximize its own objective, sharing information (variables values) with other players.

Each player, for each step, is constrained by the value of the variables taken from the other players at that step. The model applied Simplex methodology for each player's single objective optimization.

- Multi-Objective Particle Swarm Optimization (MOPSO): simulating the behavior of bird flocking, the candidate's solutions, each generations, move into the design space by following the current optimum. Turbulences may be added for increasing methodology accuracy and diversity at each generation;

- Fast-Optimizers: this category uses a two-step optimization process by means of a first phase of "virtual" optimization, in which various MO models (some of the previously described one are present in the software) used for a first generation evaluation. Than the obtained design is validated (real values are calculated), and the process moves to a second "virtual" optimization, which can exploit a different MO model;

- Hybrid optimizers: this category uses both GA with sequential quadratic programming (SQP), a single objective methodology, as one of the operators of the GA algorithm. Multi-objective problem, in the SQP optimizing stage, are treated as ε-constrained problems, i.e. one objective is minimized/maximized while the others are transformed to constraints, with eventual threshold/indifference values;

- Screening Optimization Algorithm (SanGeA), which is an hybrid algorithm in which a preliminary "screening" activity is done for identifying the most relevant variables, while the second stage finds the distribution over the Pareto front, using one of the previous GA algorithm;

- Evolution strategies, are general classes of evolutionary algorithms in which the modification between a parent generations and children improve model diversity and spread; operators such as recombination, crossover, mutation are used in ES algorithms, while the relations between generations represents a main parameter to be set up by the user, which distinguish among evolutions strategies.

Similarly to what discussed for the various types DOEs, the choice among the different optimizers will be discussed on each case study of MO optimization.

3.4 Section III: Choice Phase: Multi-Attribute Decision Making

Having identified by means of the previous stage a set of compromising solutions to the problem to be assessed, the choice among them represents the very last step of the decision making process. Choosing among different variables has to be necessarily related to the specific case study assessed, therefore provide a general scheme for all the problems would be an error. However, several methodologies have been developed for assisting qualitative and quantitative decision making process, the most relevant of them have been reviewed on paragraph 1.4.3, while the distinction between Multi Objective and Multi Attribute decision making has been provided on section 3.1.1.

The details of the methodological steps provided on section 3.1 are deepened on figure 3.7

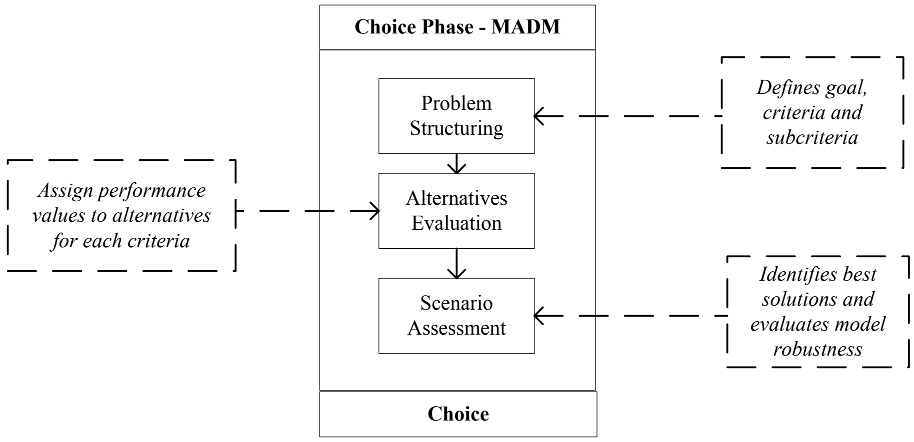


Figure 3.7: Choice Phase: substages and objectives

The methodology used in this work is the AHP/ANP, which will be assessed in detail in the following paragraph.

3.4.1 The AHP methodology

The Analytic Hierarchy Process (AHP), developed by (Saaty, 1980) consists in a structured methodology for alternatives ranking and comparison. The decision problem is structured on a hierarchical configuration (with a main goal, criteria, and subcriteria) and each level is compared to the parent one, from the bottom one (the alternatives) to the top level (the main goal). The steps of the AHP modeling involve:

- Problem structuring, refers to the stages of alternatives generation and criteria (and sub-criteria) choice, relative to the main goal selected for the analysis. The main criteria relevant for the analysis has to be chosen, avoiding the use of a too-large number of criteria and alternatives, while being
- Alternatives compared considering sub-criteria: each alternative is pairwise compared to the others, using a cardinal scale with judgment varying from 1 (equally important) to 9 (extremely more important), using intermediate values; furthermore, if direct data is available, numbers can be converted to such ordinal scale by normalizing (e.g. to the maximum value of all the alternatives), as done on the supporting software of the AHP methodologies (Superdecisions©);
- Each sub-criteria is pair wise compared considering the upper-level criteria: similarly, each sub-criteria is compared with respect to the upper-level, hierarchying those sub-levels and identifying priority vector for each criteria;
- Eventually, each criteria is compared respect the main goal.

As noted in (Saaty & Vargas, 1991), at least twelve types of problems may be addressed by the AHP, such as:

1. Setting priorities;
2. Generating a set of alternatives;
3. Choosing a best policy alternative;
4. Determining requirements;
5. Allocating resources;

6. Predicting outcomes/Risk Assessment;
7. Measure performance;
8. Designing a system;
9. Ensuring system stability;
10. Optimizing;
11. Planning;
12. Conflict Resolution

The methodology allows both quantitative and qualitative judgments, while its evolution, the Analytic Network Model, presents a similar structure of the AHP, but it allows comparing also the interaction among same-level criteria, thus permitting a decision process more similar to the real one. A brief review on application of AHP/ANP to sustainability issues is provided on Table 3.9

Table 3.9: Review on applications of AHP/ANP on sustainability-related topics

Authors	Main Object
(Singh, Murty, Gupta, & Dikshit, 2007)	Indicators for sustainable development for the steel industry are presented respected to the three pillars of sustainability. These three criteria are then aggregated using AHP, allowing identifying a unique company/industry indicator.
(Ugwu & Haupt, 2007)	Sustainability index, aggregated with AHP, is constructed for the construction industry in South Africa, allowing evaluating different infrastructure design alternatives. Relevant criteria weight are firstly determined by a panel of expert with Likert scales, while alternative are then evaluated by quantifiable and non quantifiable judgments.
(S. Perez-Vega, Salmeron-Ochoa, Hidalga, & Sharratt, 2011)	Assessing the replacement of a solvent (benzene) with another, considering economic (costs), technical (solubility, dielectric constant) and safety issues (toxicity), with sensitivity analysis
(Hsu, Hu, Chiou, & Chen, 2011)	Sustainability Balanced Scorecard is developed for the semiconductor industry by selecting criteria with a Fuzzy Delphi Method, while relative weight have been chosen using ANP
(Krajnc & Glavič, 2005)	A composite corporate sustainability index is constructed by considering social, economic and environmental criteria. Weight are calculated by using the AHP and the model is then applied on a case study
(Tseng, Lin, & Chiu, 2009)	Fuzzy AHP is used for determining the best organizational structure for promoting Cleaner Production in industrial companies, applied to a Printed Wired Board industry in Taiwan
(Nagesha & Balachandra, 2006)	Small scale industry barriers to energy efficiency are identified, by selecting and prioritizing the most relevant criteria for improving sector efficiency, basing on entrepreneur perception.
(Sirikrai & Tang, 2006)	Competitiveness of the Thailand automotive industry is analyzed by means of a structured approach using internal and external economic competitiveness indicators, aggregated with AHP
(Bottero, Comino, & Riggio, 2011)	Anaerobic Digestion, Phytoremediation and composting plant for wastewater treatment in a cheese factory are analyzed using AHP/ANP
(Chatzimouratidis & Pilavachi, 2009)	Environmental, technologic and economic criteria are used for evaluating different power plants

3.4.1.1 Pairwise Comparison

For the case of a simple three-level hierarchy, the situation is rapresented on Figure 3.8

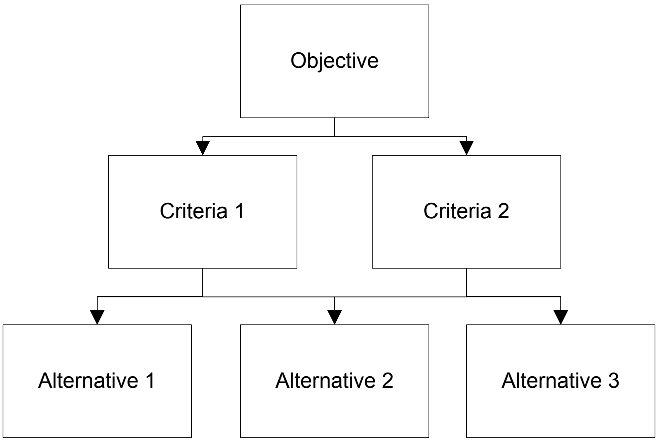
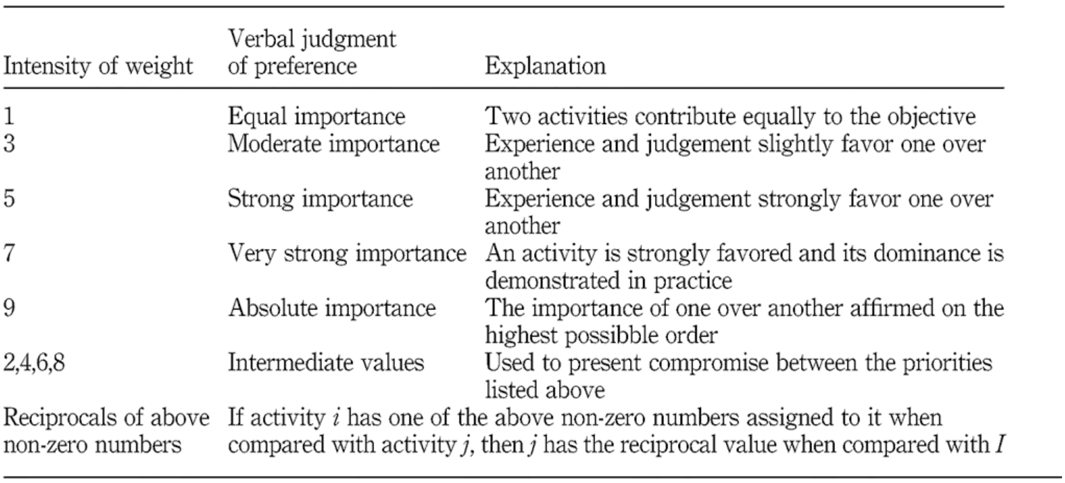


Figure 3.8. Three-level hierarchy, an example.

Alternatives 1,2,3 have to be compared to the two Criteria C1 and C2. Similarly, the weight of these two criteria to the main goals has to be also found. The main features of AHP are the use of pair wise comparison, to which each element of the hierarchy is subjected. Specifically, each element is compared with similar elements of the same level of the hierarchy, with respect to the upper level criteria. The decisor maker will have to respond to questions such as "How much alternative *i* is preferred to alternative *j*, when considering the criteria *k*? Or "How much criterion *l* is preferred to criterion *k* with respect to the main objective?". Other words, rather than "important" , might be chosen such as "preferred", "likelihood" or other user-specific words. The model allows also the use of direct data entry (for the case of quantitative information) but, given that this could not always be the case (qualitative answers), relative "Saaty Scales", (Table 3.9) are often adopted for converting qualitative information to a single value.



Intensity of weight	Verbal judgment of preference	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favor one over another
5	Strong importance	Experience and judgement strongly favor one over another
7	Very strong importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	The importance of one over another affirmed on the highest possibble order
2,4,6,8	Intermediate values	Used to present compromise between the priorities listed above
Reciprocals of above non-zero numbers	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *I*	

Figure 3.9: Fundamental Saaty Scale for pair wise comparison

The answers m_{ij} of the decisor maker are reported in matrixes in which the preference of alternative *j* compared to alternative *i* is logically the reciprocal of preference of *i* respect *j*. Those matrices are square and have a dimension equal to the number of elements of the considered hierarchic level considered. The pair wise comparison is called consistent if, given any three elements m_{ij}, m_{ik}, m_{jk}, results that:

$$m_{ik} = m_{ij} * m_{jk} \qquad (3.52)$$

For example, if alternative A1 weights double than A2 and A2 double than A3 (considering the same criteria) it should happen that A1 weight four times A3. This may not be true for qualitative judgments of the decisor maker, but AHP copes with inconsistency, allowing limited inconsistency among judgments, as it will be assessed later on. For each level of the hierarchy, a reciprocal matrix C such as the one represented on Table 3.10 are calculated-

C_i	A_1	A_2	A_3
A_1	1	m_{12}	m_{13}
A_2	$1/m_{12}$	1	m_{23}
A_3	$1/m_{13}$	$1/m_{23}$	1

Table 3.10. Example of pair wise comparison of three alternatives A respect to the criteria C_i

3.4.1.1 Priority vector

Calculation of the priority vector, i.e. the weight of each alternative for each level of the hierarchy, is based on mathematical assertions. The following procedure can be easily applied in consistent matrices. The previously–described matrix of criteria C assessment, can be seen as a matrix of ratios A, normalizing each row for the judgment of the related column, denoted as follows:

$$A = \begin{pmatrix} W_1/W_1 & W_1/W_2 & W_1/W_3 \\ W_2/W_1 & W_2/W_2 & W_2/W_3 \\ W_3/W_1 & W_3/W_2 & W_3/W_3 \end{pmatrix} \quad (3.53)$$

The multiplication of this matrix A (called the reciprocal matrix) for a column vector w, provide a column vector (product matrix per column) *nw*, where n is the rank of the matrix (three in this case). The vector w represents the relevance of each alternative considering the criteria to be determined and has to be calculated, by solving the equation:

$$(\mathrm{A} - \mathrm{nI})\mathrm{w} = 0 \quad (3.54)$$

Without entering in details on the algebra, the equation 3.54 presents a non-zero solution if and only if w is an eigenvalue of A, i.e. a root of the characteristic equation of A. Given that A present a unit rank, all eighenvalues of A are zero except one, which is equal to the maximum eigenvalue (λmax). The sum of the eighenvalues equals the sum of the diagonal elements of A, thus n.
Equation 3.54 thus becomes:

$$(\mathrm{A} - \lambda_{\mathrm{max}}\mathrm{I})\mathrm{w} = 0 \qquad (3.55)$$

The solution of this equation is any of the column of the A matrix, eventually normalized for the sum of the priority values. This simplification is true only for consistent matrices, while the real innovation of the AHP is the treatment of inconsistent judgments. It's not the aim of this work of entering in details about the calculation of the eigenvector in inconsistent matrixes, however, briefly summarizing, perturbations are allowed in the A matrix, then rose to powers, and sum of rows are normalized, calculating the eigenvector. In order to guarantee solution reliability, a consistency ratio is calculated as a ratio of a consistency index (CI), depending on the judgments, and a random consistency (RC), depending on the number of variables in the scheme. As a rule of thumb, a Consistency Ratio (C.R.) of 0.1 is allowed, while higher values mean that judgments are too inconsistent and should be modified.
From each of those matrices an order of the elements of a hierarchic level is calculated, considering each criteria, together with the resulting eigenvectors. Having found those eigenvectors, the hierarchy is calculated by considering, for each alternative, the value of each criteria's weight (the related eighteenvector) multiplied by the value of the upper criteria's eightenvectors until the main goal. Therefore, given an alternative, the final point is thus a weighed product of the values for each criteria, where the weights are the elements of the order vector of each criteria respect to the main goal.

Compared to the classic analysis, Hierarchy Analysis simplifies the decision making process by making simpler – yet more numerous – questions, also allowing more qualitative assessments.
Some authors (Marchi & Lenti, 2003) have emphasized a series of advantages of the AHP such as:

- It provides a single model easy to understand and to be adopted in various structured problems;
- It integrates deductive and holistic approaches in solving complex problems;
- It can treat a system considering interdependences and avoid the use of linear thinking by allowing partial inconsistencies among answers;

- It reflects the natural tendency of human mind to select the elements of a system among more levels and group similar ones in the same category;
- Intangibles are assessed and measured at the same level as tangible ones;
- It allows to trace back the consistency of the judgments when determining priority vectors;
- It provides a comprehensive estimation of the desiderability of each alternatives, without focusing only on the best one;
- It does not force a consensus but it synthesize the each judgments into a single value;
- It allows to refine the problem definition and develop a final judgments by means of repeated iterations (pair wise judgments);

A key element in AHP is thus rapresented by the introduction of subjective elements which could not be easily quantified and strictly dependant on decisor maker preferences. Pairwise comparison also reflects the tendency of human mind to benchmark alternatives rather than absolute judgments.

3.4.2 Analytic Network Model

A generalization of the AHP is the ANP (*Analytic Network* Process). The substantial difference between AHP and ANP is that, while the former structures the problem on a Hierarchy, with interacting vertical levels and sub-levels, the latter utilizes a “Network” approach, able to cope with more intra-level interactions (Figure 3.10).

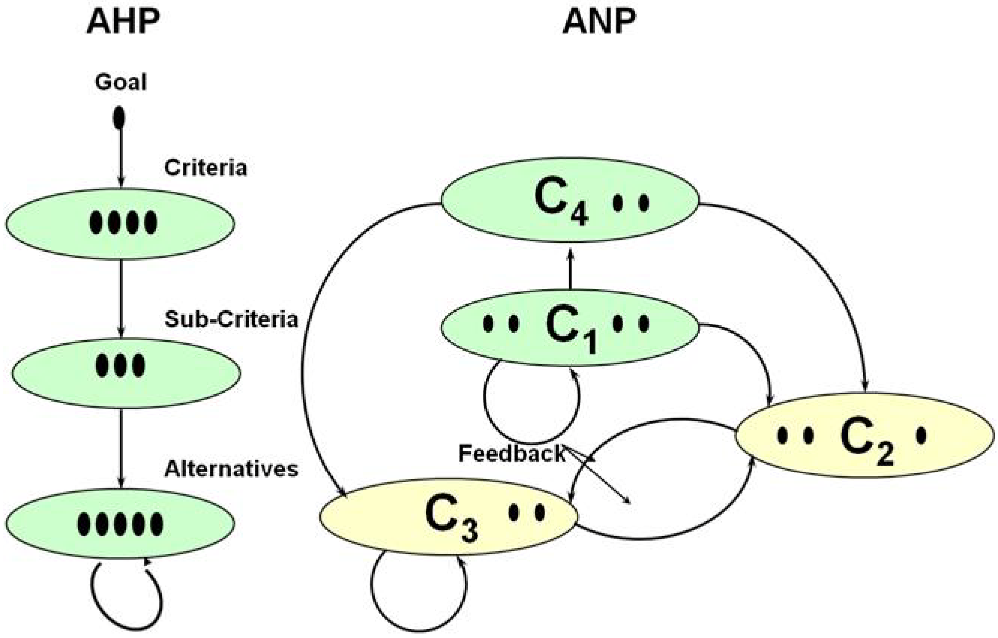


Figure 3.10: Fundamental Saaty Scale for pairwise comparison

The ANP is often used for the purposes of demand/resources allocation, as reported in many case studies in (Saaty & Vargas, 1991) and (Falcone, De Felice, & Saaty, 2009). Results of the ANP are shown in Super Matrixes, representing the interactions (i.e. the weights, i.e. the eigenvalue of the pair wise comparison calculated exactly as the AHP model). Another innovation of the ANP method is the presence of "*control criteria*", that is the most relevant element of a cluster, to which super matrixes are than weighed, usually referring to the following clusters:

- Benefits;
- Costs;
- Risks;
- Opportunities

Control criteria are used to obtain the so-called "Weighed Super matrix", used for deriving priorities for each cluster and each cluster's nodes.

The AHP/ANP methodology represents a powerful tool for coping with decision making process involving subjective judgments related to social, economic, policy and technical criteria, and has thus been chosen as a reference methodology for assisting the last stage of the decision making process

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Part II

Case Studies

4

DSS for Regional Planning

The project "CO2 non c'€", financed by the regional decree n.22/2005 of Friuli Venezia Giulia Region (Italy), was developed from January 2009 to March 2010, and represents the first application of the methodology previously discussed. The main objective of the project has been that of: "*Developing and mapping residual biomass availability in the Friuli Venezia Giulia region, identifying opportunities for utilizing such residues in Short Supply Chains (SSCs) contexts".*

Of the whole methodology, just two of the steps previously outlined have been fully used in this project, namely the intelligence and the choice stage as outlined on Figure 4.1. The Design Stage (Stage II) was applied on a simplified way, due to the presence of preliminary identified alternatives which had to be compared, as it will be explained on paragraph 4.1.

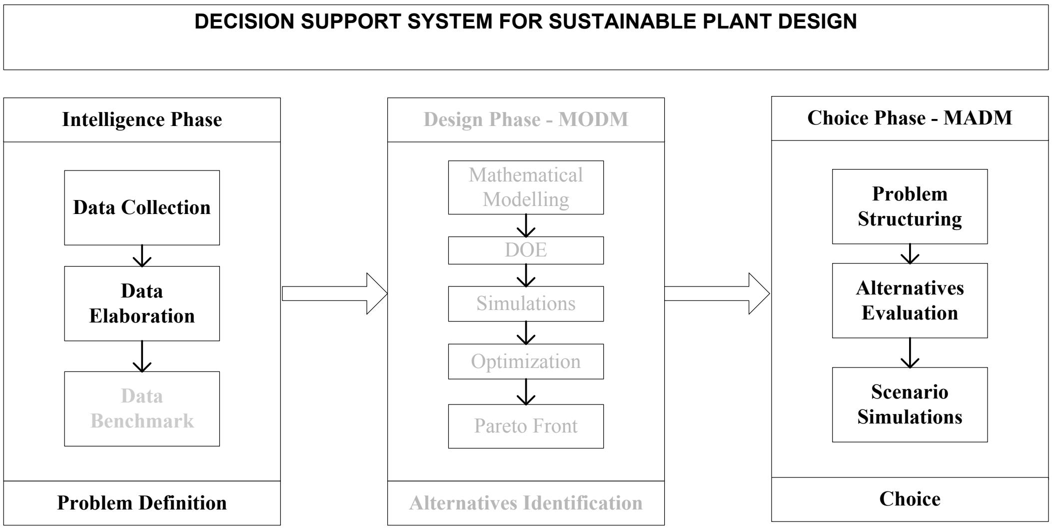

Figure 4.1: Methodological aspects of the CO2 non c'€ project

Furthermore, the application of the stage II and Stage III (Section 4.3 and 4.4), due to the broad scope of the work and the need of developing specific solutions, had been limited to the geographical context of the Comunità Collinare of the Friuli Venezia Giulia, which will be introduced on section 4.2

4.1 Stage I: Data Collection and elaboration

Data collection, referring to the broad scope of this project, had to be done by estimation. Particularly, indicators of production/consumption intensity were used for estimating biomass availability and energy consumption, in order to achieve the main goal of the project.

This stage of data collection thus presented the duplex aim of identifying:

- The residual biomass availability in the Friuli Venezia Giulia Region;
- The energy consumption of specific industries of the region, focusing on primary food transformation, industry.

Elaboration of collected data, given the way in which they had been calculated (by means of intensity indicators), consisted in developing spatial intensity indicators and excluded the benchmark stage. This step also consisted in geo-referencing of data inside the region on a municipality-basis, which allowed to “view” the data on the map support and identify opportunities of co-locating demand and supply availability.

4.1.1 Biomass availability and energy requirements estimation

The project focused on residual biomass availability. The definition of “Biomasses” covers all the materials directly or indirectly deriving from photosynthetic reactions, as vegetal materials and their derivates. Particularly, among vegetal biomasses, the following elements are considered, i.e. residual organic fraction from urban wastes, forests’ residues (woods, chips, etc.), sawmill and furniture industry’s residues (sawdust, trim cuts, pellets, logs), products in wood at their end-of-life (furniture, boxes, etc.), agricultural residues (straws, hays, leaves, etc.) and from urban management (pruning, mowing), from agro-industrial activities (oil refineries and wineries, risk husk, etc.). Animal biomasses are liquid and solid manure from farms and/or dwellings, activated sludge from water reclamation, solid and liquid animal fats, animal meal and gaseous emissions from fermented material. The recent interest in biomass plants is due to the broad range of available solutions, the flexibility of stockpiling and using biomass and the increased costs of waste disposal.

Given the agricultural activity of the Friuli Venezia Giulia region, agricultural and zoo-technical residues have been considered as major categories, with cereals’, grapes’, fruits’ and olives’ farming residues as subcategories for the former, and manure and beddings material for the latter.

Among the various industries which could have been considered for this study, the food industry represented the most relevant due to the numerous feedbacks with the agricultural one, such as geographic co-location with farms and possible residual use for energy production. Referring to the last point this industry, even if its consumption is not comparable with large manufacturing or heavy industries, represents an ideal sector for integrating with agriculture’s residues exploitation. Referring to the Friuli Venezia Giulia region, the most relevant industries which have been treated in the project are:

- Dairy industry;
- Wine production;
- Cereal drying;
- Olive oil production;
- Zoo technical Industry.

Details about data calculation (biomass availability and energy demands) may be found in (Nardin, et al., 2010)

4.1.2 Data Geo-referencing and Indicators development

The first step of data collection referred to the use of intensity indicators, which, together with production data, readily available from local association or direct interviews, have been used for calculating total biomass availability and energy demands on local basis (Municipal level). Data collected in such way, has been mapped with Map Info 8.0, the reference software for Geographic

Information System. Local maps, to be used by the regulator, has been developed for viewing industries demands and biomass availability for each single municipality, providing quantitative information on the amount of potential energy to be exploited. Furthermore, intensity indicators (Energy availability/demand per square kilometer) have been calculated to identify the municipalities with larger potential in terms of both demand and supply. Energy from agricultural residues has been mapped using MapInfo^{TM} 8.0, on a municipal-basis, depending on residues type and potentiality. Maps provided to the commitment are reported on Appendix B. Furthermore, indicators of energy potential availability have been calculated, in order to identify most promising municipalities for residual biomass' energy production. Similarly to energy availability, energy demands have been mapped on municipal basis, while also calculating intensity indicators to be used by the regulator in the planning process. Demands and availability have been used for identifying the region with more chances for developing short supply chains by means of "overlapping" obtained data as shown on Figure 4.2

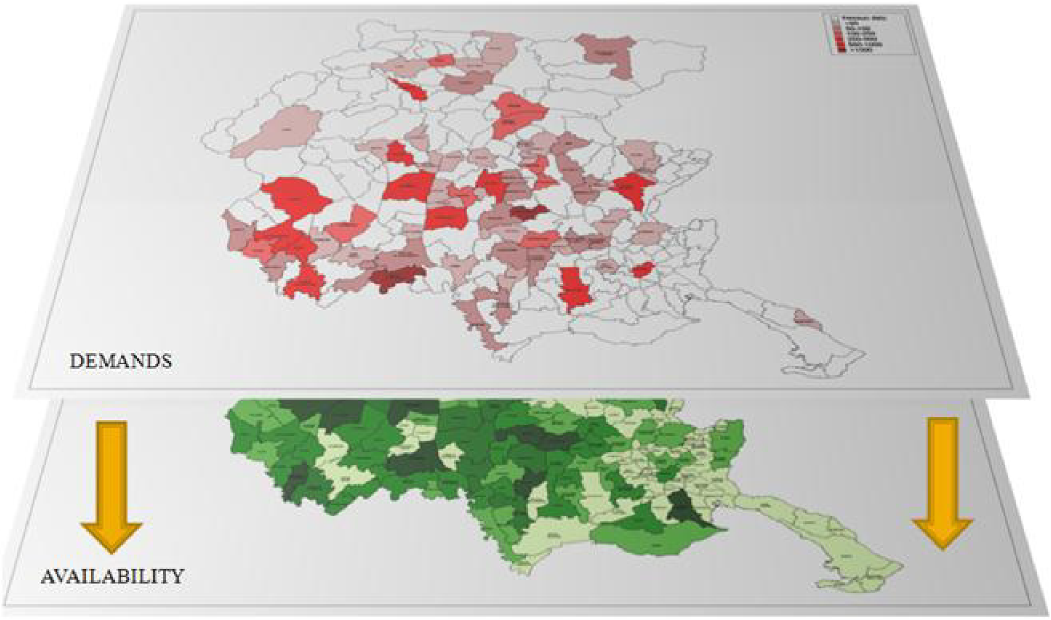

Figure 4.2: Demands and Availability overlapping for identifying short supply chains

The methodology has been applied to a series of case studies reported in (Nardin, et al., 2010); while a single application of the method considering a multi-criteria assessment is reported in the following paragraphs. Particularly, the subject of the study has been a small congregation of municipalities of Friuli Venezia Giulia, named the "Comunità Collinare del Friuli Venezia Giulia" (CCFVG).

4.2 The "Comunità Collinare del Friuli Venezia Giulia"

The consortia are made up by 16 municipalities located on Figure 4.3. The main economic activity is agricultural, while population density (145 ab/km^2) is less than the average national value (190 ab/km2) but coherent with regional value (130 ab/km2) whose economic structure is mainly agrarian (ISTAT, 2009).

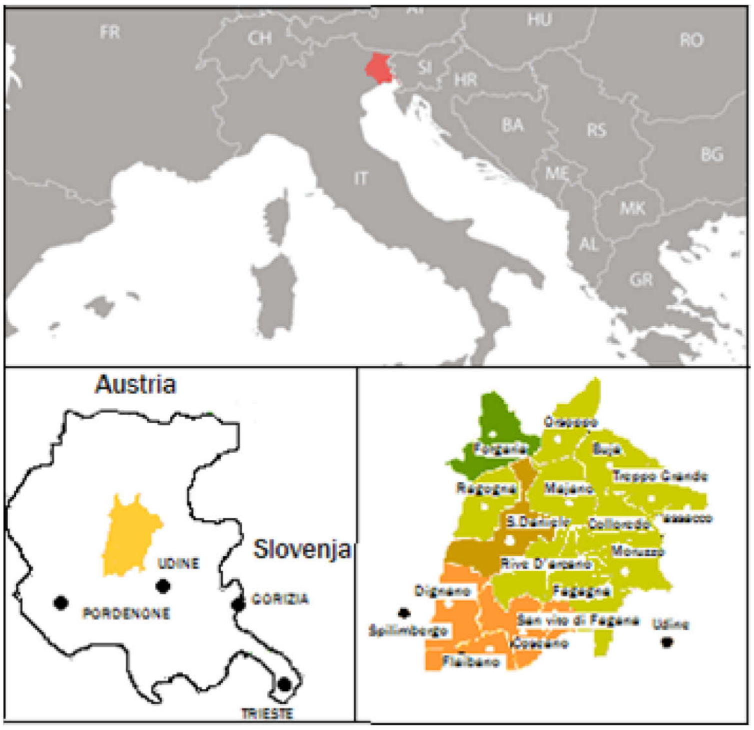

Figure 4.3: Localization of CCFVG in Friuli Venezia Giulia and Italy

4.2.1 Biomass availability

Following the national and regional statistics on (ISTAT, 2009) dividing the agricultural area in three main categories (sowables, wood cultivation and meadows), and using specific municipal data from the same national institute related to year 2000, energy potential from residual biomass of CCFVG has been estimated. Referring to the territory, the most relevant coltures have been considered, i.e.:

- Cereals such as soft/hard wheat, rye, barley, maize, oat and other cereals;
- Industrial sowables such as oil-producing as rapeseed, sunflower and soya bean;
- Woody cultivations such as grapes, olives, and fruits.

Relatively about zoo technical residues, cattle consistencies for the different municipalities of CCFVG has been calculated by accessing to the zoo technical census (ANZ, 2009) referring to average monthly values from July 2008 to June 2009, while poultry farming the values from the national agricultural census from (ISTAT, 2009) have been used. Using the conversion and productive factors previously introduced and reported in (Nardin, et al., 2010), organic fraction, producible biogas and energy availability have been estimated for each municipality of the CCFVG. Summing up energy deriving from solid residues combustion and the energy content of the anaerobically-digested zoo technical residues, the available energy is reported on Table 4.1.

Such values have also been mapped, as reported on Figure 4.4, with values and energy ranges expressed in kWh.

Table 4.1: Energy potential from biomass residues in CCFVG

Municipality	**Agricultural Biomass and Zoo technical Residues (MWh/year)**	**Anaerobic Digestion from Zoo technical Residues (MWh/year)**	**Total (MWh/year)**
Buia	20.122	1.535,8	21.849,2
Cassacco	13.477	301,2	13.701,6
Colloredo di Monte Albano	61.056	1.851,8	30.979,5
Coseano	51.566	2.540,8	50.791,1
Dignano	25.657	208,5	24.947,1
Fagagna	56.066	2.125,6	43.178,4
Flaibano	21.700	270,8	21.227,2
Forgaria nel Friuli	1.469	564,2	2.042,2
Majano	26.242	1.425,5	27.838,8
Moruzzo	17.405	462,7	16.884,3
Osoppo	3.807	215,7	4.038,7
Ragogna	13.725	478,5	14.369,8
Rive d'Arcano	32.816	1.068,9	30.642,1
San Daniele del Friuli	32.018	1.509,6	27.247,4
San Vito di Fagagna	16.785	1.292,9	16.825,3
Treppo Grande	6.867	362,0	6.878,6
Total	400.779	**16.214,5**	**422.008,6**

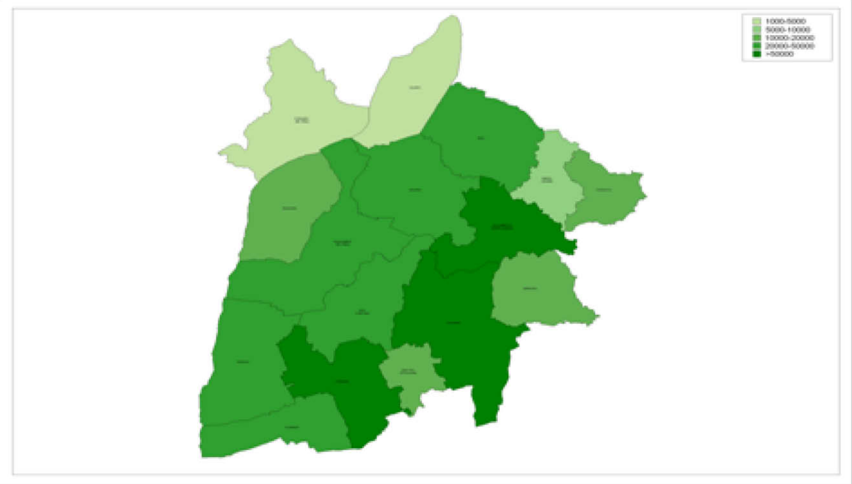

Figure 4.4: Mapping of the estimated energy availability from biomass residues in of CCFVG

4.2.2 Primary industries in CCFVG

Four main industries have been considered when assessing the energy demands of CCFVG, i.e. the dairy industry (S1); wine production (S2); primary meat production (S3); cereals industry (S4). Due to confidentiality reasons, it has not been possible to publish single companies data, while total energy consumption, divided by industry and expressed in MWh, is provided on Table 4.2. Energy demands were aggregated on municipal basis, and mapped on MapInfo 8.0. Map is shown on figure 4.5.

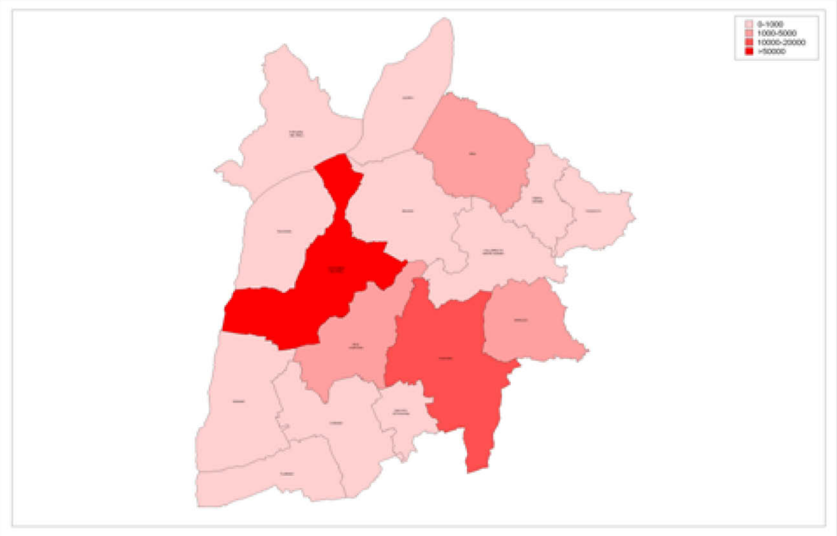

Figure 4.5: Mapping of the estimated energy consumption of CCFVG

Table 4.2: Energy demands of food industry in Comunità Collinare

	Energy Demands (MWh)				
Municipality	**S1**	**S2**	**S3**	**S4**	**S5**
Buia	1,560				1,560
Cassacco	960				960
Colloredo di M.A.	960				960
Coseano					-
Dignano	960				960
Fagagna	14,450		5,400		19,850
Flaibano	960				960
Forgaria nel Friuli					-
Majano	960			13	973
Moruzzo	1,200				1,200
Osoppo					-
Ragogna	360				360
Rived'Arcano		309	756		1,065
San Daniele del Friuli	960			112,724	113,684
San Vito Di Fagagna	902				902
Treppo Grande		938			938
Totale	24,232	1,247	6,156	112,738	144,373

4.3 Stage II: Alternatives Identification

This second step, for this case study, has been conducted basing on the results of a previous study done by the University of Udine for the same commitment. In fact, in 2008, the CCFCG commissioned the University of Udine to implement a feasibility study on the subject "Identification of the potential energy recovery from agro-industrial residues and the utilization of renewable sources inside the Comunità Collianare of Friuli Venezia Giulia". This study quantified and localized residues from agriculture production (mainly maize) and from the zoo technical breeding and slaughterhouses. Moreover, *in situ* inspection allowed to study the potential savings achievable through hydro-energy exploitation of rivers and creeks, while a preliminary audit was conducted in some of the firms of the CCFVG to identify potential 'energy fields' – which are areas characterized by complementary energy demands - in order to exploit the centralized production of a combined heating, cooling and power plant.

This study identified 5 major projects, that is:

1. Small-scale hydropower plants located in four local creeks;
2. Solar power plants partially integrated to local buildings;
3. Organic residues' recovery and anaerobic digestion in order to produce biogas, subsequently feeding a power plant located in baricentric position with respect to residues' availability;
4. Combined Cooling and Heating Plant (CCHP) fuelled by rapeseed oil growth close to the plant in the industrial area in the municipality of Fagagna;
5. Combined Cooling and Heating Plant (CCHP) fuelled by natural gas serving the food district located in the municipality of San Daniele and its local hospital.

A brief description of these alternatives is presented in the next paragraphs, together with the relative codes which will be used later on in the chapter.

Alternative 1: Small-scale hydropower plant (code A1)

The opportunity of realizing small hydro-power plants has been studied, in order to exploit the limited hydraulic jump of the CCFVG. However, the optimal sizing of these plants has to be subordinated to a more detailed study on the water flows during the year and on the possible issues which can compromise the plant's construction (e.g. marine fauna's damaging).

Alternative 2: Solar Power Plants (A2)

Power production from photovoltaic plants is an alternative applicable to all municipalities in the CCFVG, therefore it was not considered appropriate to evaluate this alternative in any single specific municipality. If anything, the potential power producible was estimated by using the region-specific average solar radiations, through the EU portal (PVGIS, 2011). The base-plant proposed to every municipality is partially integrated to the actual building structure and it does not present any tracking system. The orientation is 'South' and the angle with respect to the horizon is 35°, in order to optimize solar radiation's capture. The value chosen for the plant size was limited to 200 peak kilowatts.

Alternative 3: Anaerobic Digester and Biogas Power Plant (A3)

Fermentative processes take place in environment deprived of oxygen and are favored by the insertion of particular bacteria, which catalyze the reaction. The output of this process is a mixture of gas mainly consisting of Methane and Carbon Dioxide. The former – accounting more than the

50% of the biogas - can be used to produce power or heat. The identified solution in the study is an anaerobic digester fed by almost 1000 tones/year of food residues and maize scrap, associated with a 500 kW_e power plant. This solution promotes recovery of the agricultural, zoo technical and food-processing residues, while the plant would be located in the municipality of Rive D’Arcano, situated in a barycentric position with respect to the feeding material’s availabilities.

Alternative 4: Rapeseed oil plant (A4)

In the municipality of Fagagna, given the various energy requests in the industrial area of the commune and the agricultural vocation of the CCFVG, the possibility of installing a power plant fed by rapeseed oil has been studied. The project, which has already been given the approval by local authorities, is made up of three stages:

a) Construction of a combined heat-power plant of $4MW_e$ and external supply of bio-fuel;
b) Construction of a district heating network (estimated length: 2,5km) in order to feed the near industrial area, together with the eventual construction of absorption chilling groups, particularly needed by a company in that area;
c) Collaboration with local farmers in order to produce in the CCFVG agricultural areas the rapeseed oil needed by the plant.

Alternative 5: CCHP gas plant in San Daniele (A5)

The municipality of San Daniele is well-known on International scale for the production of its typical cured ham. The opportunity of building a centralized combined cooling and heating plant has been investigated, in order to diminish the energy costs of the 26 companies of the sector located in this area. The companies and the plant (estimated potentiality about $7MW_e$) would be linked by a district heating network (estimated length: 4 km) which would feed also the local Civil Hospital. The plant would be fuelled by a non-renewable source (natural gas), but it could represent a major opportunity for energy savings through the centralization of the energy production processes.

4.4 Stage III: MADM: Hierarchy Analysis

It can be noted from the previous paragraphs that the alternatives proposed in the study, all of them being feasible from a technical and economic viewpoint, are extremely inhomogeneous and impact in different ways over the limited territorial context of CCFVG. The latter, as it has been discussed before, has often limited budget and therefore it has to direct its choice toward the alternative which represents the optimal trade-off among the various evaluation criteria. The Analytic Hierarchy Process, as reported on chapter 3, allows breaking down the issues related to the decisional process and, after the pair wise comparison among the alternatives, it leads to the reconstruction of the model and the identification of the trade-off solution. Generally speaking, the criteria to evaluate a project in the energy and environmental field are four, that is:

1) Technical criteria: plant efficiency, productivity, useful life, etc.;
2) Economic criteria: investment cost, operative costs and revenues, payback, etc.;
3) Environmental criteria: Greenhouse effect, renewable energy, visual impact, etc;
4) Social criteria: public acceptance, side-effects on the environment, etc.

Traditional approach of the AHP is made up of mainly three stages: modeling, pair wise comparison and synthesis, which will be analyzed in the next paragraphs.

4.4.1 Problem Structuring

The main goal chosen for this analysis is the *"choice of the best solution among the ones identified for the CCFVG"*. The criteria – and their relative codification – utilized for the alternatives' evaluation are:

- C1. Energy Covering, broken up into two sub-criteria "Electrical Energy Covering" (C1a) and "Thermal Energy Covering" (C1b) which represents the ratio between the electricity (or thermal energy) produced by the alternative and the total (heat or power) requirement of the CCFVG.
- C2. Energy Conversion Efficiency. First Law's Efficiency, taking into account both the power and, in case, the thermal efficiency.
- C3. Technological Reliability, in terms of industrial development of plant technology and suppliers' and machines' availability;
- C4. Useful Life of the Plant, before it has to be dismantled or subjected to a major maintenance program;
- C5. Environmental impact, divided into two sub-criteria of 'avoided green house effect' (C5a) in terms of equivalent tones of CO_2 and 'visual impact' on the landscape (C5b);
- C6. Social acceptance of the plant, in terms of plant impact over the local community due to, for example, opinion or bias rooted in the common thinking;
- C7. Total costs of the plant, in terms of initial investment costs (C7a) and the costs and/or revenues during its operation, which are taken into account in the value of the payback (C7b);
- C8. The easiness for plant building, through the construction time value ;

The whole model used for the AHP is represented in Figure 4.7.

4.4.2 Alternatives evaluation: pair wise comparison

4.4.2.1 Evaluation of the alternatives with respect to criteria and sub-criteria

The analysis of criteria and sub-criteria highlights that, while some of them are directly or indirectly quantifiable, others, like the visual impact or the social acceptance, are not directly assessable. Anyway, the method chosen to compare the alternatives is similar, and it encompasses three stages, that is:

1. A number of i alternatives ($A_1, A_2, \dots, A_i$) has to be compared with respect to a common criteria C_j, being known, for each alternative i, the value v_i, that is a numerical value representing the performance of the alternative A with respect to the criterion C_j . For the case of quantifiable criteria, design data are utilized, while qualitative criteria have been evaluated on a 1-to-10 scale by a panel of experts. The value v_{max} is then calculated, that is the maximum v_i among the alternatives. Each v_i is divided by v_{max}, obtaining a value V_i for each i alternative, logically included from 0 to 1 (eq. 4.1).

$$V_i = v_i / v_{max}, \text{ with } 0 \leq V_i \leq 1 \qquad (4.1)$$

2. Pairwise comparison among alternatives, done by subtracting the values calculated in the previous stage. For example, the comparison between two alternatives A_1 e A_2 is done by calculating the difference between V_1 and V_2 and considering its absolute value (eq. 4.2)

$$X_{12} = X_{21} = |V_1 - V_2| \qquad (4.2)$$

3. Relate the values obtained in the previous stage – through proportion and considering eventual approximation by excess or defect – to the 1 to 9 scale, as traditionally used in the AHP model for pair wise comparison

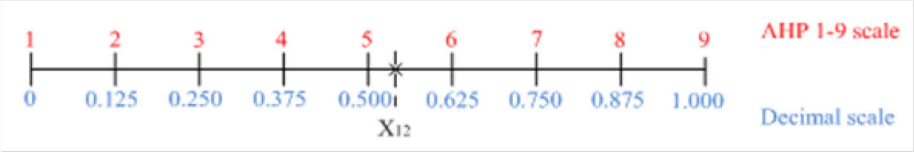

Figure 4.6: Nomogram used to refer the decimal values to the 1-9 scale

Qualitative and quantitative[1] data used for the pair wise comparison are shown in Table 4.3.

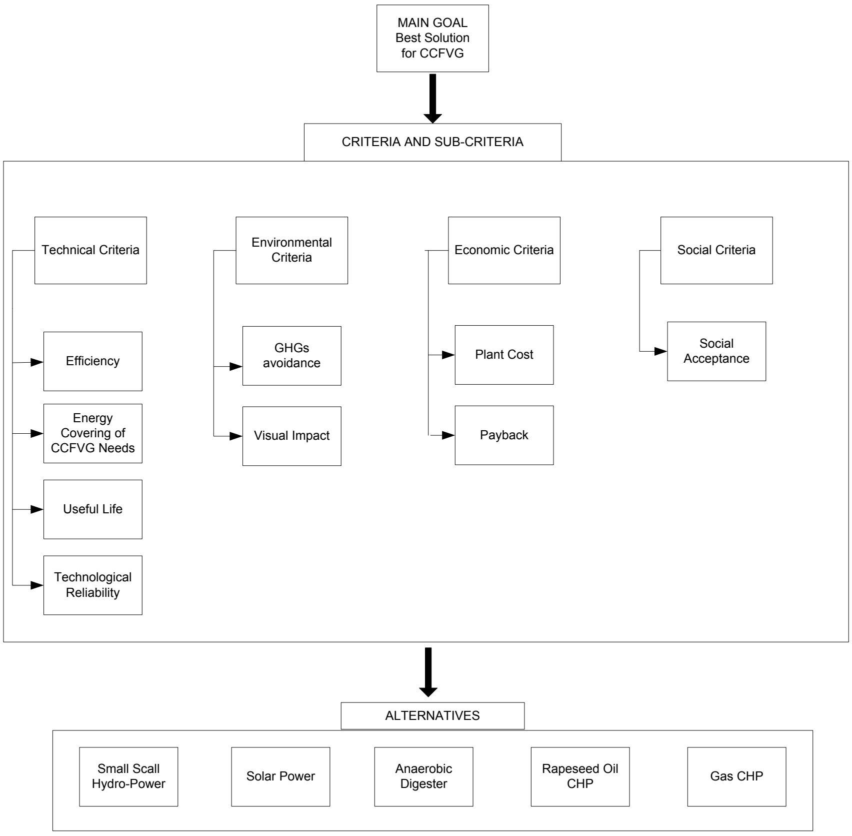

Figure 4.7: Reference system model used for the AHP

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[1] Economic calculations were made considering the average Italian costs of electricity, equal to 0.14 €/kWh, and that of Natural Gas, the common source used for heating, equal to 0.35 €/Nm^3, fixing the exchange rate at 0.75 €/$. No incentives were considered. Technical data were taken from the above-cited feasibility study.

Table 4.3: Synthesis of the quantitative and qualitative features of the identified alternatives

		Alternatives				
	U.M	**A1**	**A2**	**A3**	**A4**	**A5**
Quantitative Criteria						
Nominal Power	kW_e	325	200	500	4,000	7,000
Efficiency	%	73.00	10.00	39,00	80.95	86.00
Electricity Output	kWh/y	1,440,000	200,500	3,504,000	32,000,000	49,056,000
Thermal Output	kWh/y	0	0	0	23,048,000	35,810,880
Time to Build	months	12	3.5	20	30	18
Greenhouse effect avoided	kg $CO2_{eq}$	110,275	792,000	1,927,200	15,270,744	23,507,145
Plant Cost	$	1,316,250	952,500	4,007,438	3,903,750	10,125,000
Payback	years	8.7	45.4	10.9	6.1	10.5
Useful Plant Life	years	30	20	10	20	15
Qualitative Criteria						
Technological Reliability	-	5	6	3	10	8
Social Acceptance	-	8	10	6	5	5
Visual Impact	-	6	3	1	9	10

After having found these values, each pair of alternatives are compared by subtraction, as it is done in Table 4.4. The alternatives are firstly ranked (from the maximum value of V_i, necessarily equal to 1, to the minimum value reported) to better suit the following comparison, which led to the values to be used in AHP pair wise comparison scheme.

Table 4.4: Example of pair wise comparison among alternatives using decimal values

	A5	A3	A4	A1	A2
A5	1				
A3	1 - 0.4 = 0.6	1			
A4	1 - 0.39 = 0.61	0.4 - 0.39 = 0.01	1		
A1	1 - 0.13 = 0.87	0.4 - 0.13 = 0.27	0.39 - 0.13 = 0.26	1	
A2	1 - 0.09 = 0.91	0.4 - 0.09 = 0.31	0.39 - 0.09 = 0.3	0.13 - 0.09 = 0.04	1

Eventually, values inside Table 5 are referred to the traditional 1 to 9 scale of the AHP. In this example, the comparison between the combined cooling heating and power plant (A5) and rapeseed oil plant (A4) lead to a value of .61, which is 'translated' in a factor 6 in the AHP scale (Figure 4.8). With regards to the total investment costs, therefore, the A4 is 'strongly to very strongly' more important than A5, which was predictable because of the more than halved investment needed for A4. The confrontation between the various alternatives leads to the matrix represented in Table 4.5.

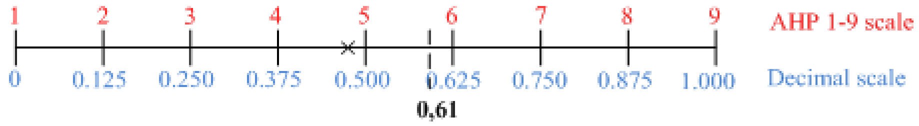


Figure 4.8: Example of referring the decimal distance among alternatives to the 1-9 scale

Table 4.5: Example of matrix for alternatives' comparison with respect to the sub-criteria 'Plant Cost'

C7a	A1	A2	A3	A4	A5
A1	1	1	3	3	8
A2		1	3	3	8
A3			1	1	6
A4				1	6
A5					1

All the pair wise comparisons among alternatives are transcribed in Table 4.7, together with the consistency ratio (C.R.) which always resulted less than 0.1.

4.4.2.1 Evaluation of sub-criteria with respect to the above criterion

In order to evaluate the weight of the sub-criteria with respect to the above criterion, given the little number of judgment needed, the traditional AHP 1-9 scale has been directly utilized by the evaluation panel. Results are shown in Table 4.6.

Table 4.6: Synthesis of the pair wise comparisons among sub-criteria with respect to the above criteria

C1	C1a	C1b
C1a	1	3
C1b		1

C5	C5a	C5b
C5a	1	3
C5b		1

C7	C7b	C7b
C7a	1	1/3
C7b		1

4.4.2.2 Scenario analysis: evaluation of criteria with respect to the main goal

During this last stage of the comparison, weights of the single criteria with respect the main goal have not been fixed in order to make the method more consistent to the real decisional process. In real situations, as a matter of fact, the decision maker could present different backgrounds, and therefore a unique synthesis would have not faithfully reflected the common decisional process. Specifically, three different viewpoints have been considered:

- Technical/Engineering viewpoint, favoring solutions with higher efficiencies, yields and reliability, together with affordable expenses;
- Administrative viewpoint, which favors the alternatives more feasible from the economic perspective, together with social acceptable solutions for the community;
- Environment-friendly viewpoint, supporting solutions characterized by minimum environmental impact and generally unaware of the technical and economical features.

- The weights associated to each single criterion with respect to the final goal are presented in Table 4.8.

Table 4.7: Synthesis of the pair wise comparisons among the alternatives (A1-A5) with respect to the chosen criteria and sub-criteria

C1a	A1	A2	A3	A4	A5
A1	1	1	1	1/6	1/9
A2		1	1/2	1/6	1/9
A3			1	1/6	1/8
A4				1	1/4
A5					1

C.R. 0.0406

C1b	A1	A2	A3	A4	A5
A1	1	1	1	1/6	1/9
A2		1	1	1/6	1/9
A3			1	1/6	1/9
A4				1	1/4
A5					1

C.R. 0.0266

C2	A1	A2	A3	A4	A5
A1	1	7	4	1/2	1/2
A2		1	1/4	1/8	1/8
A3			1	1/5	1/5
A4				1	1
A5					1

C.R. 0.0313

C3	A1	A2	A3	A4	A5
A1	1	1/2	3	1/5	1/3
A2		1	3	1/4	1/3
A3			1	1/7	1/5
A4				1	3
A5					1

C.R. 0.0392

C4	A1	A2	A3	A4	A5
A1	1	4	6	4	5
A2		1	4	1	2
A3			1	1/4	1/2
A4				1	2
A5					1

C.R. 0.0240

C5a	A1	A2	A3	A4	A5
A1	1	1	1	1/6	1/9
A2		1	1/2	1/6	1/9
A3			1	1/5	1/8
A4				1	1/4
A5					1

C.R. 0.0354

C5b	A1	A2	A3	A4	A5
A1	1	3	5	1/3	1/4
A2		1	3	1/6	1/7
A3			1	1/7	1/8
A4				1	1/2
A5					1

C.R. 0.0457

C6	A1	A2	A3	A4	A5
A1	1	1/3	3	3	3
A2		1	4	5	5
A3			1	2	2
A4				1	1
A5					1

C.R. 0.0250

C7a	A1	A2	A3	A4	A5
A1	1	1	3	3	8
A2		1	3	3	8
A3			1	1	6
A4				1	6
A5					1

C.R. 0.0405

C7b	A1	A2	A3	A4	A5
A1	1	7	1	1	1
A2		1	1/7	1/7	1/7
A3			1	1/2	1
A4				1	2
A5					1

C.R. 0.0173

C8	A1	A2	A3	A4	A5
A1	1	1/3	3	6	3
A2		1	5	8	5
A3			1	4	1/2
A4				1	1/4
A5					1

C.R. 0.0493

Table 4.8: Judgments of criteria with respect to the main goal following a triple viewpoint

Technical/Engineering		Administrative		Environment-friendly	
CRITERIA	***Rating***	***CRITERIA***	***Rating***	***CRITERIA***	***Rating***
Efficiency	10	Total Costs	10	Environmental Impact	10
Energy Covering	9	Environmental Impact	10	Social Acceptance	8
Total Costs	7	Social Acceptance	9	Efficiency	5
Technology Reliability	7	Time to build	7	Energy Covering	5
Time to build	6	Efficiency	5	Useful life	5
Useful life	5	Energy Covering	5	Technology Reliability	5
Environmental Impact	3	Useful life	4	Time to build	5
Social Acceptance	1	Technology Reliability	4	Total Costs	3

These values are used in the same fashion of the previous criteria, following the method presented in 4.4.2.1 and 4.4.2.1, and lead to the matrixes shown in Tables 4.9

Table 4.9: Criteria's comparison with respect to the main goal: three different perspectives

	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	1/2	3	4	6	7	3	3
C2		1	3	5	7	8	3	4
C3			1	3	4	6	1	2
C4				1	3	4	3	1/2
C5					1	3	1/4	1/3
C6						1	1/6	1/5
C7							1	2
C8								1

Criteria’s Comparison by the engineering perspective

	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	1	2	2	1/5	1/4	1/5	1/3
C2		1	2	2	1/5	1/4	1/5	1/3
C3			1	1	1/6	1/5	1/6	1/3
C4				1	1/6	1/5	1/6	1/3
C5					1	2	1	3
C6						1	1/2	3
C7							1	3
C8								1

Criteria’s Comparison by the administrative perspective

	C1	C2	C3	C4	C5	C6	C7	C8
C1	1	1	1	1	1/5	1/3	1/3	1
C2		1	1	1	1/5	1/3	3	1
C3			1	1	1/5	1/2	3	1
C4				1	1/5	1/3	3	1
C5					1	3	7	5
C6						1	5	2
C7							1	1/3
C8								1

Criteria’s Comparison by the environmental perspective

4.4.3 Choice Stage

Alternatives were assessed following the criteria presented with respect to the triple perspective, namely engineering, environmental and administrative. The AHP's results are shown in Table 4.10 and figure 4.9.

The AHP revealed that the alternative A5 – the CCHP plant serving the food district of San Daniele – appears to be the most relevant choice among the opportunities identified for the CCFVG. The three different perspectives analyzed revealed that no significant variation was reported in the relative comparison among alternatives. The only change happened in the engineering perspective, whose ranking revealed a preference of the small-scale hydropower plant (A1) respect, the photovoltaic systems (A2).

Table 4.10: Criteria's comparison with respect to the main goal: three different perspectives

Alternatives	Ideals	Normal	Raw
A5	1	0.319022	0.134646
A4	0.839627	0.267860	0.113052
A1	0.630775	0.201231	0.084931
A2	0.438030	0.139742	0.058979
A3	0.226143	0.072145	0.030449

Alternatives' ranking with respect to the engineering perspective

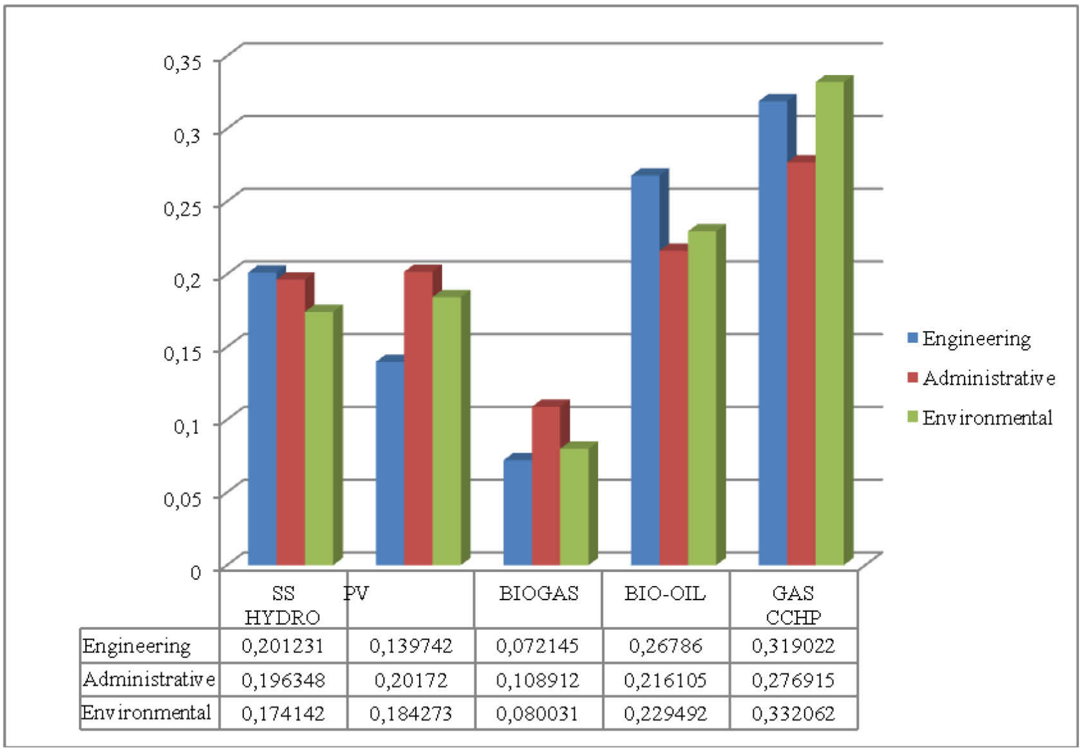
Alternatives	Ideals	Normal	Raw
A5	1	0.276915	0.107203
A4	0.780401	0.216105	0.083661
A2	0.728456	0.201720	0.078092
A1	0.709057	0.196348	0.076013
A3	0.393307	0.108912	0.042163

Alternatives' ranking with respect to the administrative perspective

Alternatives	Ideals	Normal	Raw
A5	1	0.332062	0.133237
A4	0.691112	0.229492	0.092082
A2	0.554937	0.184273	0.073938
A1	0.524428	0.174142	0.069873
A3	0.241014	0.080031	0.032112

Alternatives' ranking with respect to the environmental perspective

Concluding, the AHP was used to evaluate alternatives for energy reduction or renewable energy's exploitation for a group of municipalities in the North East of Italy. Decisional process in such limited contexts needs to address those alternatives which better suits the different objectives of the stakeholders. The AHP proved to be a useful tool to assess various alternatives, even if these latter were characterized by different performances with respect to the criteria utilized. Qualitative data were assessed by a panel of experts, while quantitative data – taken from the design specifications – were referred to (i.e. divided by) the actual values registered in the municipalities. This operation, even if it logically does not affect the AHP results – is useful to assess the alternatives not only in general terms, but for site-specific study, which is a precondition of every decisional process in local contexts. Among the various alternatives proposed in the study, the choice of building a CCHP plant serving the local food district and the civil hospital in the municipality San Daniele appeared to be the best choice for each of the three viewpoints considered in the analysis, namely engineering, administrative and environmental. The preference accorded to a rationalization project, rather than to other options introducing renewable sources, confirm the actual need of comprehensive multi-criteria studies of the various alternatives before undertaking projects in the energy and environmental industry.



	SS HYDRO	PV	BIOGAS	BIO-OIL	GAS CCHP
Engineering	0,201231	0,139742	0,072145	0,26786	0,319022
Administrative	0,196348	0,20172	0,108912	0,216105	0,276915
Environmental	0,174142	0,184273	0,080031	0,229492	0,332062

Figure 4.9: Alternatives ranking depending on the various perspectives

5

DSS in the Health Care Sector

The health-care industry, especially in the Italian framework, represents one of the major expenditure item in national budget and has therefore attracted the attention of various spending' reduction initiatives. Given the relevance of its core business, the focus has shifted on non-medical activities, such as facility management, which, in its branch of energy management, has been the main focus of the application of the methodology previously outlined. The project was commissioned by the Regional Health Care Agency ("Agenzia per la Sanità del Friuli Venezia Giulia") and it has been undertaken from January 2009 to December 2010.

The methodology has been applied to the regional health care sector of Friuli Venezia Giulia. Of the whole methodology presented on chapter 3, this project focused on the first two stages (the intelligence and the design stage), as shown on Figure 5.1.

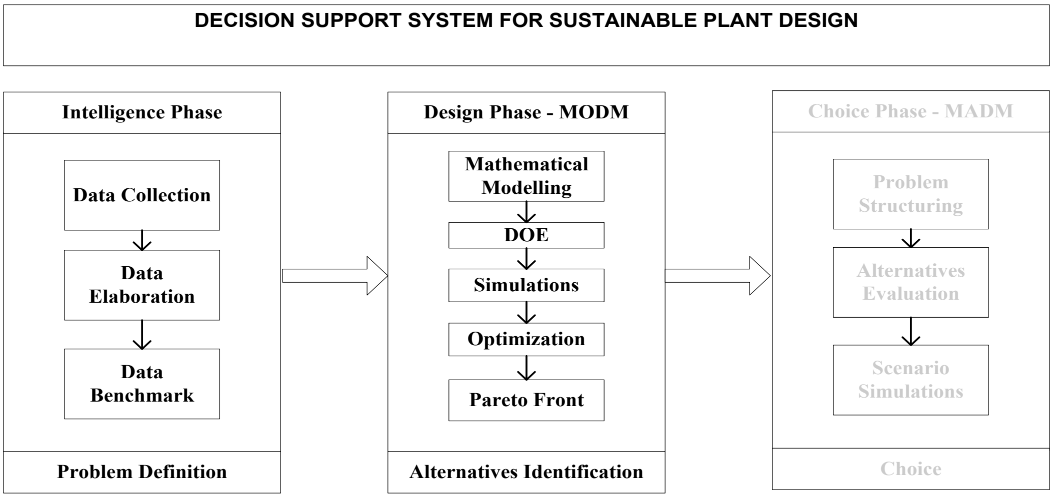


Figure 5.1: Methodological aspects treated in the section

Data collected during the first stage, by means of survey and walking-through audits, were elaborated in order to identify performance indicators (general or sector-specific), which have been later on benchmarked with internal and external sources. The details of the intelligence stage are assessed on section 5.1. Design stage, together with some other opportunities identified during the assessment, followed the mathematical model presented on chapter 5.2. Considering specific features of the health-care sector, the Multi-Objective design of CHP and PV plants has been studied, comparing results for various facilities, as shown on section 5.2.1.

5.1 Stage I: Data collection, elaboration and benchmark

The intelligence stage has been conducted in the three different moments of data collection, elaboration and benchmark. The sampled companies, coherently with the current national health-care facilities 'organizational structure, have been divided depending their regional relevance, thus considering regional-relevance structures, named "Aliened Ospedaliere" (AO), local facility "Ospedali Civil" (CH), health care buildings with research institutes, (RI), and other buildings with different functions (OB). The final sample is made up of 21 buildings, among which 3 AO, 12 CH e 2 Ri and 4 OB. The final sample has been selected depending on structures' relevance in terms of dimensions and energy consumption, while accounting also for few smaller facilities to broaden the sample.

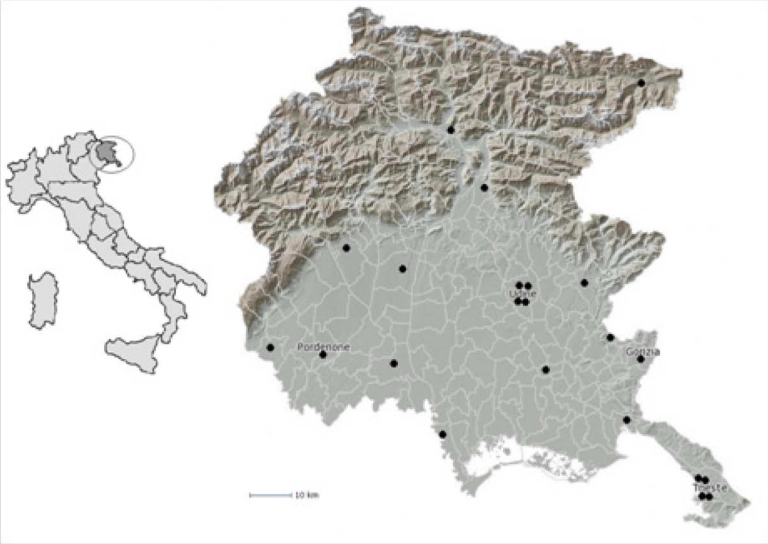


Figure 5.2: Map of the sampled health-care facilities

5.1.1 Literature analysis

The Health-Care industry presents technological and managerial features particularly relevant when assessing actions for rationalizing energy consumption and production. The simultaneous presence of heating, indeed, cooling and power loads, together with water, steam and technical gas usages, make this industry particularly relevant, also given the need of continuous 24/7 operation. Among the relevant literature in this field, it has been distinguished among single-structure study and broader assessments in multi-facility contexts. Referring to the former, the focus of the study is often on combined heating, cooling and power plants, with specific references on benchmarking internal combustion engines and gas turbines (Renedo, Ortiz, Manana, & Siliò, 2006), risk assessment related to power price (Al-Mansour & Kožuh, 2007), energy and exergy efficiency of CCHP as a function of power prices (Ziher & Poredos, 2006), the installation of a CCHP system with process steam-recovery and utilization of back pressure turbines and absorbing machines (Meckler, 2002); CCHP technologies considering distributed generation (Medrano, Castell, Fontanals, Castellón, & Cabeza, 2008), and varying the energy loads (C.Z. Li, 2009), or by applying linear programming models for optimizing plant sizing (Ennio Cardona, 2006). Programming models have been broadly used for optimal configuration of energy plants (Arcuri, Florio, & Fragiacomo, 2007) (Yoshida, Ito, & Yokoyama, 2007) Lozano, 2009, Shu et alia, 2007). Particular interest has been given to lighting equipment, particularly referring to medium/long term verification of energy savings, (Lee, 2000), or to the possible adoption of Fuel Cells (Bizzarri & Morini, 2004), and system of natural venting comparing with traditional mechanical-driven systems (Lomas & Ji, 2009). (Khodakarami, Knight, & Nasrollahi, 2009) simulated the usage of various insulating material assessing the energy savings, while Herrera (2003) applied the principles of pinch technology (Herrera, Islas, & Arriola, 2003) for modeling heat flows. Eventually, referring to the single technologies to be used in the health-care system for reduction consumption , many studies have been made for using solar energy, for producing heat for sterilization/lighting and water distillation (Merkle, 1994), of for conditioning by means of absorbing systems (Wolpert, Nguyen, & Riffa, 200).

On the second category, the research on relevant samples of health-care facilities has been considered. Szklo et al. Have analyzed and computed energy consumption indicators in the Brazilian Health Care industry, depending on facility function, type and size (Szklo, Soares, & Tolmasquim, 2004). Similarly, authors have assessed the potential energy savings in small-size facilities of the Scottish health-care system (Murray & O. Pahl, 2008). (Hirst, 1982) assessed a total of 48 health-care facilities, quantifying the possible energy savings, while Adderley et alia assessed some opportunities in the Welsh health care system (Adderley, O'Callaghan, & Probert, 1987), and then assessing/optimizing the realization in other structures (Adderley, O'Callaghan, & Probert, 1988). (Santamouris, Dascalaki, Balaras, Argiriou, & Gaglia, 1994), conducted a study on 40 facilities in the Greek Health care system, quantifying specific consumption and savings from various actions. Among the academic researches, relevant interest on the health-care has been associated by public and private institution, such as the British Health Service (NHS, 1996) the American Society for Healthcare Engineering (ASHE) with the Healthcare Energy Project (ASHE, 2003) and the “Centre for Analysis and Dissemination of Demonstrated Energy Technologies” (CADDET, 1997). In the EU, the project “EU-Hospitals” (VV.AA., 2005) referred to 5 different facility in five different European countries, identifying indicators for energy usage and opportunities for improving such performances.

5.1.2 Data collection

Data collection has been done by a written questionnaire followed by a facility’s inspection done by external personnel. The questionnaire has been divided in four parts, with quantitative and qualitative information, codified for the following assessment – related to:

A. General information about the *structure*, such as geographical location, area and volumes, beds, qualitative description of the building (age, renovations, type, etc.) and some qualitative information about the presence of a dedicated team for energy management (QA1), company’s personnel (QA2) or plant-related personnel QA3), consumption data availability (QA4), periodic maintenance (QA5), supplementary energy meters (QA6), renewable energy access (QA7), optimization of power (QA8) and fossil fuel (QA9) contracts;
B. Information about the building, with questions about the shielding systems (QB1), insulation of roof/walls (QB2) and related recent modifications (QB3), interstitial

condense phenomena (QB4), questions related to windows panels such as double glazing (QB5), thermal braker (QB6), metal (QB7), plastic (QB8) or timber (QB9) frames, and the insulation of rolling-shutters boxes (QB10), people detectors (QB11), and bio-climatic architecture (QB12);

C. Qualitative and quantitative data, referring to fuel used (primary and emergency), while questions have been made about differentiated metering of consumption (QC1), availability of energy supply contracts (QC2), plant partitioning (QC3), district heating networks (QC4), high efficiency generators (QC5), CHP (QC6) or CCHP (QC7) plants, heat pumps (QC8), heat recovery systems (QC9), solar panels (QC10), waste treatment plants (QC11) or other renewable-fuelled plants (QC12). Furthermore, questions about decentralized regulation of temperature (QC13), external maintenance of heat plants (QC14), PV plants (QC15), and high-efficiency lightings systems (QC16) and related automation (QC17). Eventually, the presence of power factor correction (QC18) and external management of electrical plants (QC19). Differentiated data on fuel/power consumption, together with related economic prices have also been considered in this section.
D. Plant data, referring to heat and power plants configuration (e.g. layout) and related operating parameters (type, vector fluid, temperature, flows, pressures, operating hours, maintenance costs).

The inspection of each structure has been made by visual, walking-through audit done by external personnel relating toe the entire supply-utilization energy cycle, with criticalities identified for four main areas (A-D), such as:

A. Energy supply: unsuitable emergency heating/cooling plants (IA1); obsolete boilers/chilling plants (IA2); low efficiency boiler/chillers (IA3); missing emergency voltage transformer (IA4); missing/obsolete power factor adjusting systems (IA5); Medium Voltage or Low-Voltage devices to be adjusted (IA6); non-ringed power system (IA7); unutilized cogenerator (IA8); external plants not protected by atmospheric agents (IA9); no emergency fuel on boilers (IA10);
B. Distribution and transmission system: limited maintenance team (IB1); low maintenance status (IB2); unsuitable air treatment plants (IB3); and cables to be renewed (IB4)
C. Energy losses related to the structure (IC1) or the distribution system (IC2);
D. Emergency systems: limited emergency fuel storage (ID1); non-adequate emergency systems (ID2); absence of UPS (ID3)

5.1.2.1 Qualitative results

Qualitative questions results, using the codes and the main sections previously reported are now assessed. Results of the first and second area (general information about the structure and building) are shown on Figure 5.3a e Figure 5.3b, while answers related to energy data are shown on Figure 5.4

Most of the structures (85%) does not have a dedicated team to energy issues, while general employees have not been informed on energy-related thematic on 65% of the sampled companies, with similar percentages (50%) for plant-related personnel. Such low information system is confirmed by the absence of specific metering of energy loads, while consumption data availability has been positive for most of the sample, with some exception for third-party managed facilities. Periodic maintenance is done regularly by all of the sampled companies, while a significant percentage presented an evaluation/optimization of power-supply contracts, with opposite results when discussing about fuel supply. Most of the sampled companies (65%) stated not to have the access to renewable-energy market.

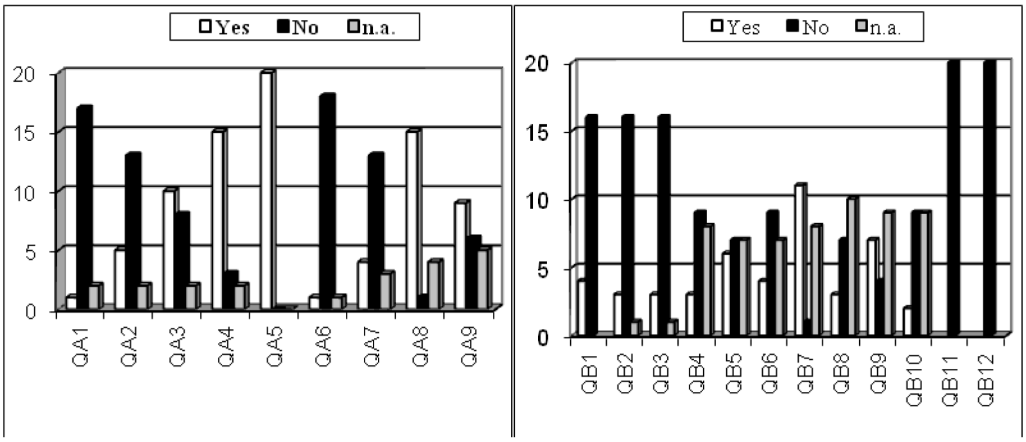


Figure 5.3 a) and b): Qualitative answers about energy management and building

Results about the civil building show a homogeneous sample. Most of the structures do not present shielding systems, recent insulation of rooftops or walls, thermal braker glazing or PVC/wood frames. Low-emitting and double glazing are indeed present in some of sampled companies, while rolling-shutter boxes are insulted for about half of the facilities. No automation in cooling/heating plants or bio-climatic architectures has been detected. Relatively to the primary fuel used, most of the buildings are fuelled by natural gas (75%), followed by fuel oil (20%). About one fifth of the companies do not present an emergency fuel, referring to which diesel and fuel oil are the most preferred sources. Eventually, the answers related to the third section highlighted a relevant uniformity among the sample, with negative answers to differentiated metering systems (80%), district heating network (90%), CHP (90%) or CCHP (95%) plants, heat recovery plants (55%), solar panels (95%), waste treatment (95%), automation of lighting equipment (80%) or internal temperatures management (70%), and utilization of renewable energy (95%), specifically PV plants (100%). Positive answers were associated to availability of energy contracts (70%) and third parties management of heat (90%) and power (70%) plants.

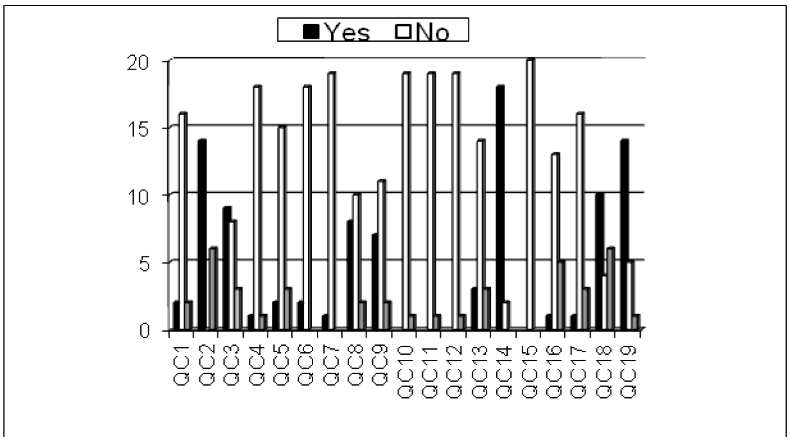


Figure 5.4: Questionnaire answers: qualitative data

5.1.3 Data assessment

Data collected in third and fourth part of the questionnaire, completed and verified by the information taken during the inspection, have been classified in three categories. Structural data such as heated area (S) and beds number (PL) have been considered, while power (Q_e) and heating (Q_h) loads; eventually power capacities as supplied (P_e), boilers' heat capacity (P_t). Values from the sampled structures are reported on Table 5.1, and allowed to calculate indicators for internal external benchmark as it will be later assessed.

Table 5.1 Data collected on the sampled facilities

	S *[m²]*	*PL*	Q_e *[MWh]*	Q_t *[MWh]*	P_t *[MW]*	P_e *[MW]*
AO1a[2]	73.500	179	6.250	5.538	11,63	1,385
AO1b	66.267	740	15.663	35.274	22,68	5,040
AO2	132.190	999	19.983	49.937	18,60	3,995
AO3	113.698	416	11.889	22.672	14,51	1,960
CH1	58.333	205	9.419	21.122	11,00	2,000
CH2	25.035	192	3.120	8.578	7,62	0,550
CH3	14.803	93	2.085	4.348	3,99	0,420
CH4	18.266	105	1.195	4.571	4,19	0,490
CH5	15.610	96	1.174	3.633	5,14	0,420
CH6	34.953	350	4.292	10.585	5,78	0,750
CH7	33.180	156	2.633	8.037	9,84	0,443
CH8	27.923	210	5.843	10.728	8,11	0,824
CH9	11.576	42	858	2.920	2,92	0,228
CH10	19.581	76	2.419	4.228	4,58	0,460
CH11	32.819	186	3.971	9.693	6,99	0,878
CH12	38.720	264	2.793	13.665	11,63	0,736
RI1	47.520	150	9.330	18.298	11,16	1,868
RI2	21.000	175	3.588	3.390	6,13	0,652
OB1	10.571	107	717	2.696	2,05	2,000
OB2	1.610	0	38	448	0,651	0,028

Correlation analysis between static data showed particularly interesting trends of both power and heating consumption, referred to both heated area and hospital beds, as shown on Figure NUM and NUM. Regression curves thus identified provided information to both regulator and single structure

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[2] This facility is made up by two different buildings in two different part of the city. Thus have been considered independently ..

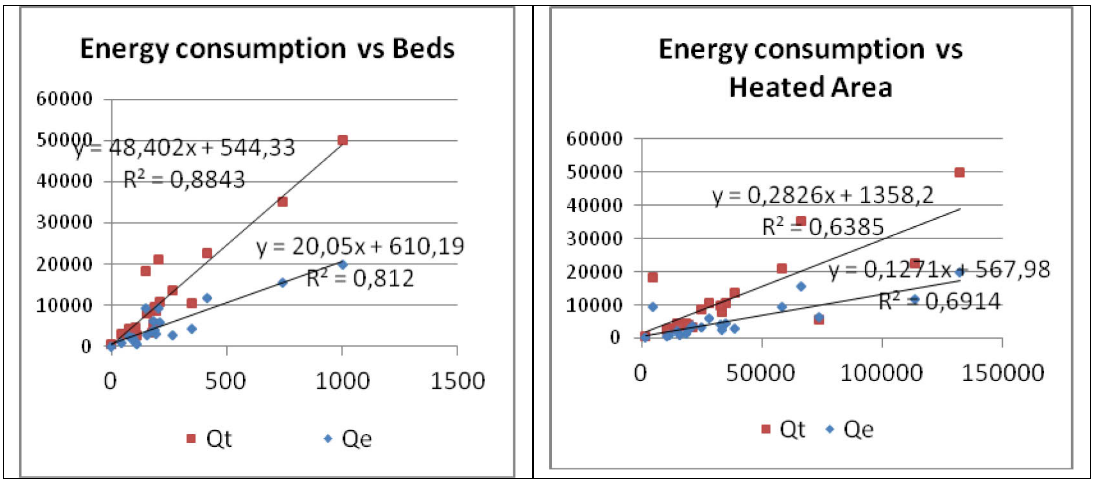


Figure 5.5: Correlation between Energy Consumption (in kWh) and number of beds (a) and heated area (b, in m^2*)*

5.1.3.1 Energy loads and costs

Energy loads, referring to both power and heat consumption, allow to a first benchmark the sampled companies. Using the common conversion factors, data on Table 5.1 shows that heat loads are 2/3 (on average) of total energy consumption, while related expenditure is equally divided, as a consequence of a higher specific power costs.

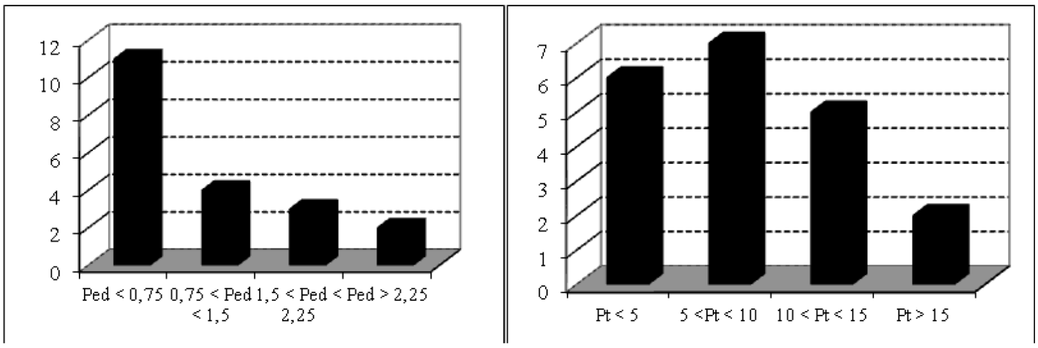
Heat and power loads of each structure are shown on Table 5.2, showing that costs data are not completely availably, especially when referring to heat loads due to the presence of an external management of energy supply, and thus no availability of energy bills.

Table 5.2: Aggregated values of energy consumption and costs for sample facilities

	total MWh	**Power**	**Heat**	**k€**	**Power**	**Heat**
AO1a	11.788	53%	47%	n.d.	n.d.	n.d.
AO1b	50.938	31%	69%	n.d.	n.d.	n.d.
RI1	6.978	51%	49%	n.d.	n.d.	n.d.
CH1	30.540	31%	69%	n.d.	n.d.	n.d.
OB1	3.413	21%	79%	283	41%	59%
CH2	11.698	27%	73%	437	n.d.	n.d.
OB2	486	8%	92%	n.d.	n.d.	n.d.
CH3	6.433	32%	68%	585	52%	48%
AO2	69.921	29%	71%	4.986	45%	55%
CH4	5.767	21%	79%	n.d.	n.d.	n.d.
CH5	4.807	24%	76%	427	43%	57%
CH6	14.876	29 %	71%	n.d.	n.d.	n.d.
CH7	10.670	25 %	75%	n.d.	n.d.	n.d.
CH8	16.571	35%	65%	n.d.	n.d.	n.d.
AO3	34.562	34%	66%	3.018	53%	47%
CH9	3.778	23%	77%	303	36%	64%
CH10	6.647	36%	64%	619	55%	45%
CH11	13.664	29%	71%	1.166	47%	53%
CH12	16.458	17%	83%	964	41%	59%
RI2	27.628	34 %	66%	2.130	57%	43%

Installed capacities

Eventually, descriptive data on energy capacities are reported for each sampled facility. Installed capacity have been reported for heating (P_{TI}) and cooling (P_{FI}) loads as nominal capacity of the boilers and chillers (Unit of Measurement: kW), excluding, when available redundant/ emergency plants, and available power loads (P_{ED}), i.e. the maximum value of power supplied to the user on a contract basis, which is often different from the effective used power (P_{EI}), depending on real loads from the building. Results on the first three values are shown on Figure 5.6 a, b e c.



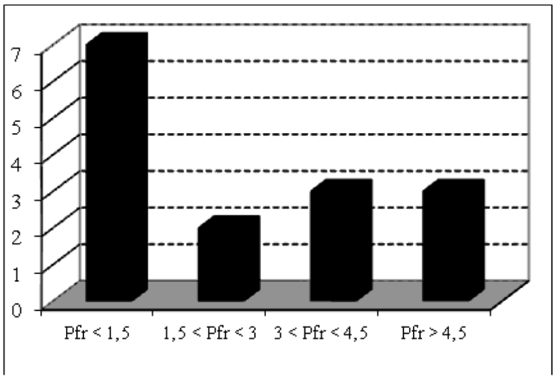


Figure 5.6: Classification of sampled companies for Available Power (a, P_{ed}), Heating (b, P_t) and Cooling (c, P_{ff}) capacities

5.1.4 Data elaboration and benchmark

Data reported in the previous paragraphs allowed to calculate the most relevant indicators for internal and external benchmark of company's performances in terms of energy consumption. Most used normalization factor to be used for indicators' calculation in available literature are:

- The heated area of the building;
- The number of beds of the facility;

Therefore, the following primary indicators have been calculated:

1. Heat loads per unit of heated area (kWh_t/m^2);
2. Power loads per unit of heated area (kWh_e/m^2);
3. Heat loads per unit of bed (kWh_t/PL);
4. Power loads per bed (kWh_e/PL)

Other than this fundamental indicators, further combination of data previously determined have been calculated, such as:

5. Heat loads per installed heat capacity (kWh_t/KW_t);
6. Power loads per supplied power capacity (kWh_e/KW_e);
7. Energy expenditure (heat and power) per unit of heated area (€/m^2);
8. Energy expenditure (heat and power) per beds (€/PL);
9. Heat costs per heat loads (€/kWh_t);
10. Power costs per power loads (€/kWh_e);
11. Power loads per heat loads.

5.1.4.1 Energy loads per unit of heated area

Crossing the heating and power loads with effective heated area allowed to calculate a primary indicator of energy efficiency of health-care structures. Referring to heating loads, the average regional value has been calculated as about 288 kWh/m^2 (standard deviation 99 kWh/m^2, maximum value at 532 kWh/m^2, minimum at 75 kWh/m^2). Power loads spatial intensity showed an average regional value of 121 kWh/m^2 (SD 54). Those two parameters have been compared with similar case studies taken from the international literature assessed in the previous paragraphs as shown on Figure 5.7).

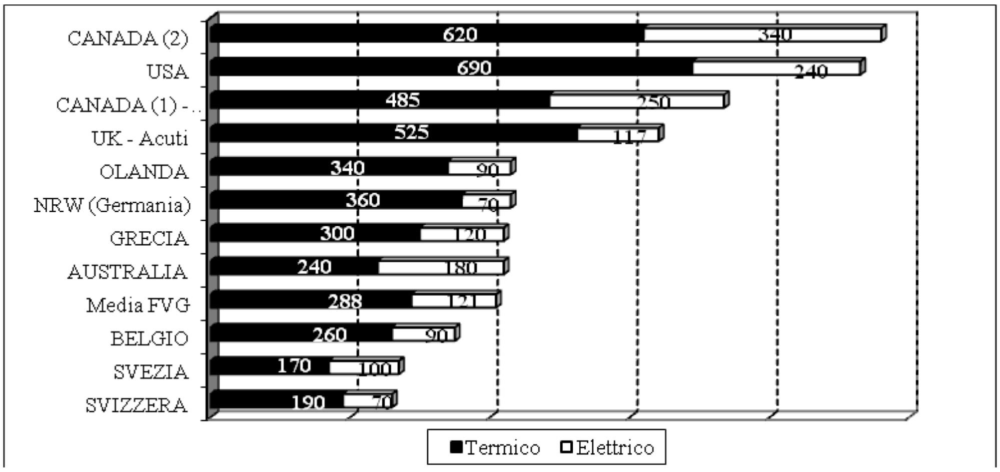


Figure 5.7: Heat and Power Loads spatial intensity (UM: kWh/m²), international benchmark

5.1.4.2 Energy loads per bed

Similarly, primary energy consumption per unit of bed has been benchmarked. This indicator, together with the latter, has been broadly used in literature. The values identified show average heat consumption per bed equal to 49,2 MWh/PL (SD 22,16), while power intensity is 23,52 MWh/PL (SD: 13,47). This indicator has been benchmarked with various studies worldwide, as shown on Figure 5.8

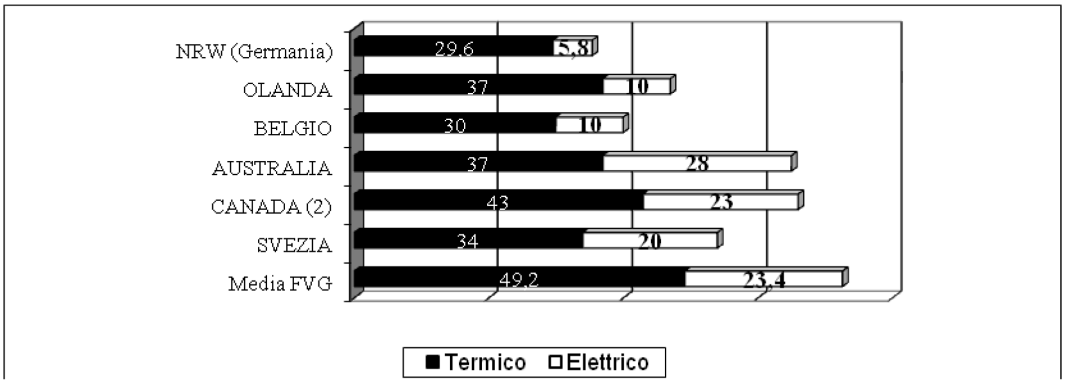


Figure 5.8: Heat and Power consumption per bed (MWh/PL), international benchmark

From the assessment of the last figure, it is shown that regional indicators are, on average, higher than literature references, especially referring to energy consumption per beds, while specific consumption per heated area is similar to other case studies. From such considerations, it appears that an evaluation of the effective utilization of beds per unit of heated are should be taken into consideration by the facilities' manager.[3].

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[3] An indicator for assessing the effective occupation of beds has been calculated by (Szklo et alia, 2004), assessing the ratio between beds and occupied area. For large structures (> 450 PL) the value is equal to 0,0048 PL/m^2, while for other structures with lower beds this indicator is 3 times bigger (0,0163 PL/m^2). The same indicator, calculated for the regional context, shows a lower value for both the AOs (0,0075 PL/m^2), and the other structures (0,006 PL/m^2).

5.1.4.3 Energy intensity indicators: a synthesis

On Table 5.3 the fundamental indicators for benchmarking energy consumption of health-care sampled facilities are reported.

Table 5.3: Energy consumption intensity indicators for the sampled companies

	heat		Power	
Code	kWh/m2	kWh/PL	kWh/m2	kWh/PL
AO1a	75,34	30.937	85	34.919
AO1b	532,34	47.671	236	21.164
AO2	377,75	49.986	151	20.005
AO3	199,41	54.501	105	28.58
CH1	241,01	68.579	161	45.949
CH2	342,63	44.676	125	16.253
CH3	293,68	46.747	141	22.421
CH4	196,83	34.241	65	11.386
CH5	232,72	37.842	75	12.235
CH6	275,08	27.471	123	12.263
CH7	323,25	68.753	79	16.882
CH8	384,20	51.087	209	27.821
CH9	252,22	69.518	74	20.27
CH10	215,94	55.637	124	31.828
CH11	295,36	52.115	121	21.349
CH12	352,91	51.76	72	10.58
RI1	161,42	19.371	171	20.504
RI2	385,07	121.991	198	62.637
OB1	255,07	25.2	68	6.697
OB2	373,14	n.d.	32	n.d.
Average	288,27	49.218	120,72	23.355

5.1.4.4 Energy costs

Energy costs, related to effective energy consumption, are to be assessed in this paragraph. Average heat price in the sampled companies is equal to 60,15 €/MWh (SD 8,42), while power price is equal to 145 €/MWh (standard deviation: 16,23). Details on the costs of the various structures are shown on Table 5.4. Average energy costs amounted to 13.5 c€/kWh (SD 1.6) with descending trend as a function of heat loads (diminishing between 6 and 14%), while increasing with low power needs (+10/15%).

Table 5.4: Average thermal energy costs of sampled facilities

Code	Heat Load	UM	kWh$_{eq}$	Expenditure	€/MWh
AO1a	563.16	m3 CH4	5.537.740	n.d.	n.d.
AO1b	3.587.440	m3 CH4	35.276.493	n.d.	n.d.
AO2	5.078.188	m3 CH4	49.935.515	€ 2.730.537,00	54,68
AO3	2.305.649	m3 CH4	22.672.215	€ 1.432.120,03	63,17
CH1	1.850.000	kg f-oil	21.120.833	n.d.	n.d.
CH2	751.345	kg f-oil	8.577.855	n.d.	n.d.
CH3	442.118	m3 CH4	4.347.494	€ 283.255,69	65,15
CH4	464.881	m3 CH4	4.571.330	n.d.	n.d.
CH5	369.436	m3 CH4	3.632.787	€ 244.902,45	67,41
CH6	1.076.362	m3 CH4	10.584.226	n.d.	n.d.
CH7	1.090.728	m3 CH4	10.725.492	n.d.	n.d.
CH8	1.091.001	m3 CH4	10.728.177	n.d.	n.d.
CH9	296.924	m3 CH4	2.919.753	€ 193.924,32	66,42
CH10	430.011	m3 CH4	4.228.442	€ 279.147,11	66,02
CH11	985.766	m3 CH4	9.693.366	€ 620.721,37	64,04
CH12	1.196.900	kg BTZ	13.664.608	€ 571.552,69	41,83
RI1	296.924	kg BTZ	3.389.882	n.d.	n.d.
RI2	1.602.808	kg BTZ	18.298.725	€ 924.232,31	50,51
OB1	274.206	m3 CH4	2.696.359	€ 168.024,44	62,32
OB2	45	l diesel	447.769	n.d.	n.d.

5.1.4.5 Statistical analysis: determination of correlation matrix

Correlation analysis has been done for the data and indicators computed in the previous sections. Particularly, the following correlations have been assessed:

- Total energy consumption and building heat loads (kWh vs. m^2);
- Total energy consumption and beds number (kWh vs. PL);
- Power and heat intensity related to heated area (kWh$_e$/m^2 vs. kWh$_t$/m^2);
- Power and heat intensity related to beds number (kWh$_e$/P.L. vs. kWh$_t$/P.L.);
- Heat and power loads related to the installed capacity (kWh$_e$/kW$_{disp}$ vs. kWh$_t$/kW$_{inst}$)
- Spatial intensity relate to total heated area (kWh/m^2 vs. m^2);
- Energy intensity referred to beds number and beds number (kWh/PL vs. PL);
- Power specific costs and total power loads (€/MWh$_e$ vs. kWh$_e$);
- Heat specific costs and total heat loads (€/MWh$_t$ vs. kWh$_t$);
- Power heat loads and average power factors (€/MWh$_e$ vs. cosφ).

Some of the correlation among such indicators is shown on Table 5.6-

Table 5.5: Average power costs of sampled facilities

Code	Consume [kWh]	Costs [€]	€/MWh
AO1a	6,250,589	€ 831,505.89	133.03
AO1b	15,661,203	€ 1,963,495.94	125.37
AO2	19,985,173	€ 2,692,373.95	134.72
AO3	11,889,467	€ 1,585,730.14	133.37
CH1	9,419,603	€ 1,327,892.95	140.97
CH2	3,120,522	€ 437,241.43	140.12
CH3	2,085,117	€ 301,855.34	144.77
CH4	1,195,569	€ 182,163.46	152.37
CH5	1,174,595	€ 182,163.46	155.09
CH6	4,292,172	€ 606,685.98	141.35
CH7	2,633,629	€ 377,761.05	143.44
CH8	5,842,439	€ 847,445.94	145.05
CH9	851,347	€ 143,504.06	168.56
CH10	2,418,955	€ 340,131.94	140.61
CH11	3,970,826	€ 545,482.76	137.37
CH12	2,793,160	€ 393,372.53	140.83
RI1	3,588,246	€ 506,311.96	141.1
RI2	9,395,573	€ 1,206,008.00	128.36
OB1	716,617	€ 115,141.63	160.67
OB2	37,819	€ 7,498.56	198.27

Table 5.6: Correlation analysis among data and indicators

Variable 1	Variable 2	Correlation Index (R^2)
Total kWh	Heated Area	0.76
Total kWh	Beds	0.89
kWh$_e$/m^2	kWh$_t$/m^2	0.2
kWh$_e$/P.L	kWh$_t$/P.L	0.65
kWh$_e$/kW$_{disp}$	kWh$_t$/kW$_{inst}$	0.11
kWh/m^2	m^2	0.03
kWh/PL	PL	0.003
€/MWh$_e$	kWh$_e$	0.81
€/MWh$_t$	kWh$_t$	0.3
€/MWh$_e$	cosφ	0.51
kWh$_t$/m^2	GG	0.04
kWh$_t$/PL	GG	0.07

5.1.4.6 Identification of facilities' criticalities

The inspection at the structures allowed identifying some criticalities, divided in four categories previously identified. Results are shown on Table 5.7. Most relevant problems are related to low efficiency boilers/chillers (IA3, 71% of the sample) , medium/high voltage devices to be adequate (IA5, 61%), together with related cables (IB4, 71%).

Table 5.7: Issues emerged during the facility inspection

Supply	**N°**	**Distribution**	
IA1	4	IB1	1
IA2	1	IB2	1
IA3	15	IB3	3
IA4	4	IB4	15
IA5	5	**Energy Losses**	
IA6	13	IC1	18
IA7	3	IC2	15
IA8	1	**Emergency Services**	
IA9	1	ID1	1
IA10	6	ID2	2
		ID3	4
		ID4	2

5.2 Stage II: Alternatives Identifications

Having identified, assessed, and benchmarked companies in the regional health-care field, the next step has been that of identifying possible solutions for reducing their environmental impact, especially regarding to the energy field. Multi-objective model for optimal sizing of CHP plants has been used in this case study. The model has been used for two case studies among the sample facilities. The first one is a medium-sized (350 beds and 36.000 m^2) civil Hospital, while the second one is a smaller-size assistential facility (105 beds and 10.000 m^2) whose details are reported on Appendix C, providing synthesis tables referring to facility general information and indicator analysis, coherently with the previous approach.

5.2.1 Multi-Objective analysis

Having reviewed the sampled companies, the multi-objective model which has been structured on chapter 3 has been applied. The preliminary step to the optimization process referred to the following parameters selection:

- **Initial DOE**: in order to define the initial candidate solutions to be assessed by the optimizer, it was chosen, for easing the scheduler, to manually add an initial set of candidates (five solutions) which are feasible (non constraints broken); the other candidates of solutions have been chosen by using the Incremental Space Filter (ISF) algorhytms, as introduced on chapter 3
- **Scheduler**: Non-Selective Genetic Algorhytms (NSGA –II) has been chosen as the optimization algorhytms. Such scheduler, compared to other optimizer tested during the simulations, proved to be extremely powerful because of the intrinsic elitists properties and the capacity of adapting the scheduler options to the pareto front movements;
- **Simulator parameters**: a broad range of optimization parameters could have been chosen at this stage. Scenario analysis was then considered.

5.2.2 Case study 1

Four main scenarios have been considered:

- Scenario 1: base scenario, using current market-related economic parameters (fuel/electricity prices and trends, incentives value and trends) and most recent power/heat loads of the structure;
- Scenario 2: similar to scenario one, but considering a sensible increase in bio-oil prices, much more subjected to volatility when compared to the other economic parameters;
- Scenario 3: base scenario nullifying the contribution of national incentives on renewable energy or energy efficiency;
- Scenario 4: base-load scenario, considering increased consumption regarding heat and power loads (+25%), assessing the robustness of the scenario 1 solutions;
- Scenario 5: base-load scenario, but limiting the analysis to profitable (NPV>0) and environmental-friendly solutions (TIER>0), also constraining the maximum capital cost required.

5.2.2.1 Scenario 1

Applying the multi-objective model with current, market-related prices and most-recent consumption data allowed to identified the following Pareto Front of trade-off solutions between most economically efficient solutions (maximum Net Present Value, NPV) and best-performing solutions in terms of environmental impact assessment (maximum Total Environmental Impact Reduction, as defined on Chapter 3). Pareto Front is reported on Figure 5.9, together with explanatory information reporting plant type and size emerging from the Multi-Objective assessment. The Pareto-Front (initial DOE: 50 designs, number of generations 200) has been calculated after a simulation running of about 2 hours. The Front appears to be enough accurate to broadly describe the possible plants to be installed. Increasing simulation time and design/generation number could have improved front accuracy, but it wasn't considered necessary at this stage of plant design.

The solutions front is divided in 4 main parts:

- In the first part (upper left part of Figure 5.9) the most profitable solutions (in terms of NPV) are reported. Not surprisingly, most remunerating installations are those leaded by a 900-kW Bio-Oil power plants, which is close to the threshold (1MW) below which the renewable-fuelled plants receive a consistent incentive for power production (0.28 €/kWh). Power efficiency represents the second main driver in plant choice, given that, despite the high capital costs (a value of about 4 10^3 €/kW has been chosen as specific capital costs), most of the first set of solutions comprised FC as plant. A variable capacity of PV plants (0 – 200 kW) was also considered in this range. Relevant emissions of Bio-oil ICE, however, compromise the environmental performances of this solution set.
- In the second set (middle), a broad range of solutions was identified, in which the economic redditivity is still dominated by the bio-oil plants, but a diminishing in the

related capacity (200 – 600 kW) leads to a sensible improvement of environmental impact reduction. Such reduction is compensated by the utilization of Gas Turbine Plants, providing useful power and heat while relating a sensible reduction in emissions, and thus impact.

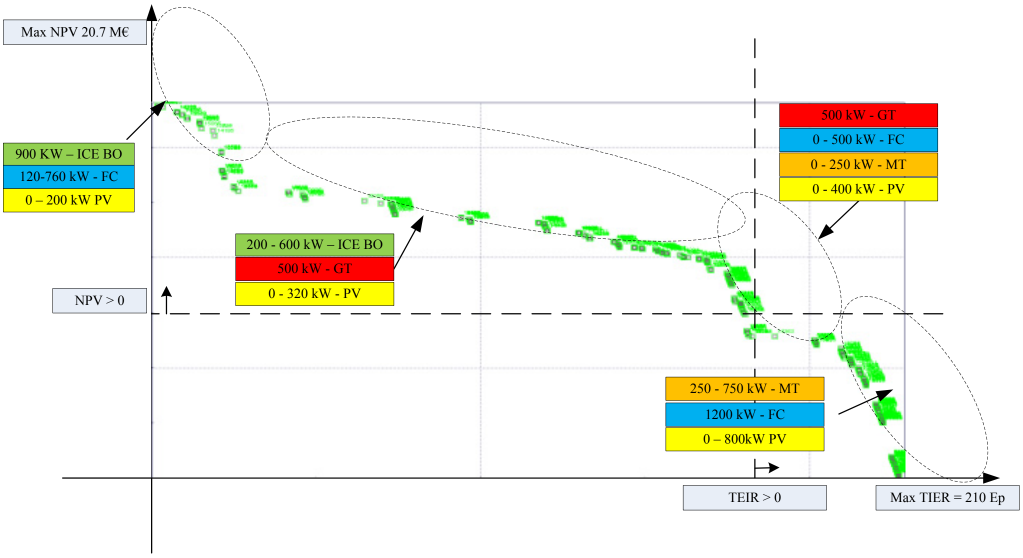

Figure 5.9: Pareto-Front for Multi-Objective plant design of Case Study, Scenario 1

- The third set of solution (upper-right), accounting for both profitable (NPV >0) and environmental friendly (TIER > 0) solutions will be addressed in particular;
- The last set of solutions (bottom-right) accounts for lest impacting solutions (including micro-turbines, fuel cell and PV plants), whose profitability is however less than 0, i.e. they represent potentially not-profitable investment.

The relevance of the upper-right quadrant is clear, due to the fact that the solutions candidates in this area presents both features of economic viability and environmental impact reduction, i.e. they produce less emissions than they currently avoid. Such quadrant is zoomed on Figure 5.10

Combination of Gas Turbines, Fuel Cells, and PV modules allows both to satisfy at least the 80% of company's power and heat needs, while being contemporary profitable and environmental friendly, thus reducing total emissions. Inside each of the four ranges identified in this quadrant, variability is led by PV module sizes, which, as expected moves from more profitable solutions to a less impacting range of solutions. As expected, maximum NPV is considerably reduced (from 20.7 to 5 M€), and so the environmental benefits (from 210 to 26 Eco-Points).

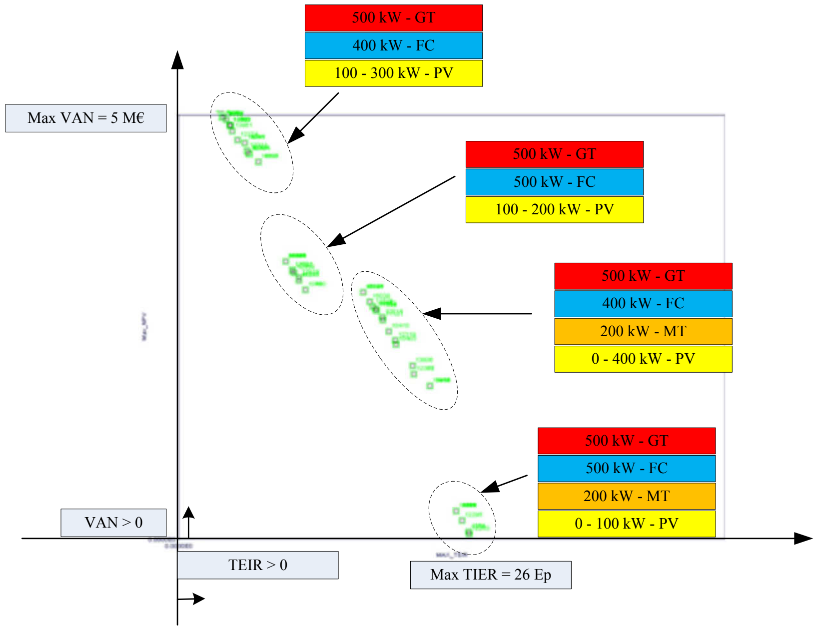

Figure 5.10: Pareto-Front for Multi-Objective plant design of Case Study, Scenario 1, Details

Eventually, it’s interesting to assess how the simulator operates (Figure 5.11) assessing increasingly various types of solutions improving the performances (economic and environmental), before converging to the Pareto Front which, given that both objectives are subjected to maximization processes, is represented by the most “external” points of the solution space.

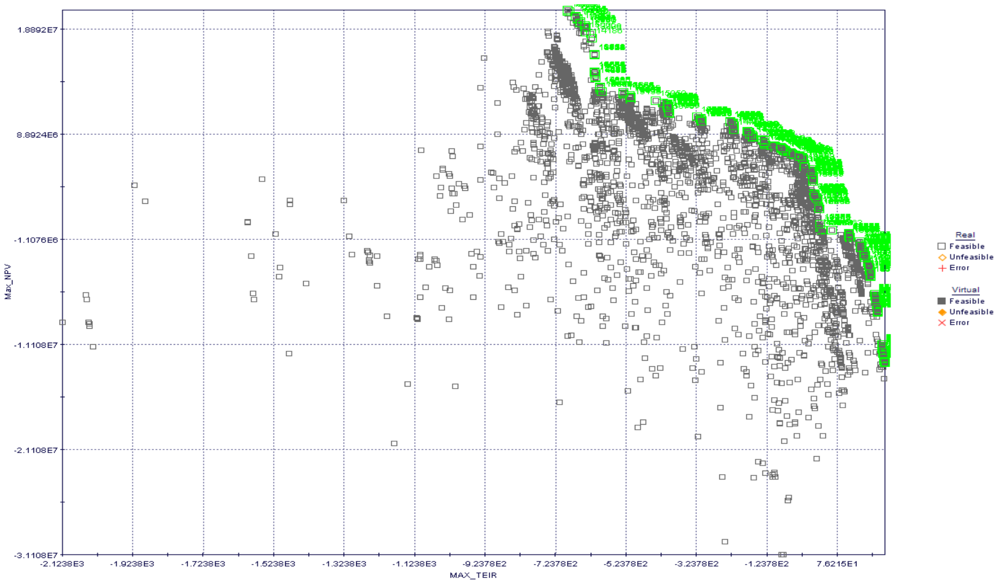

Figure 5.11: Solution space and Pareto-Front of Case Study, Scenario 1, Details

5.2.2.2 Scenario 2

In this scenario, bio-oil prices were varied from 0.85 €/kg to 1.2 €/kg, in order to assess the robustness of the scenario in the event of an increase in bio-oil price. Results are shown on Figure 5.12.

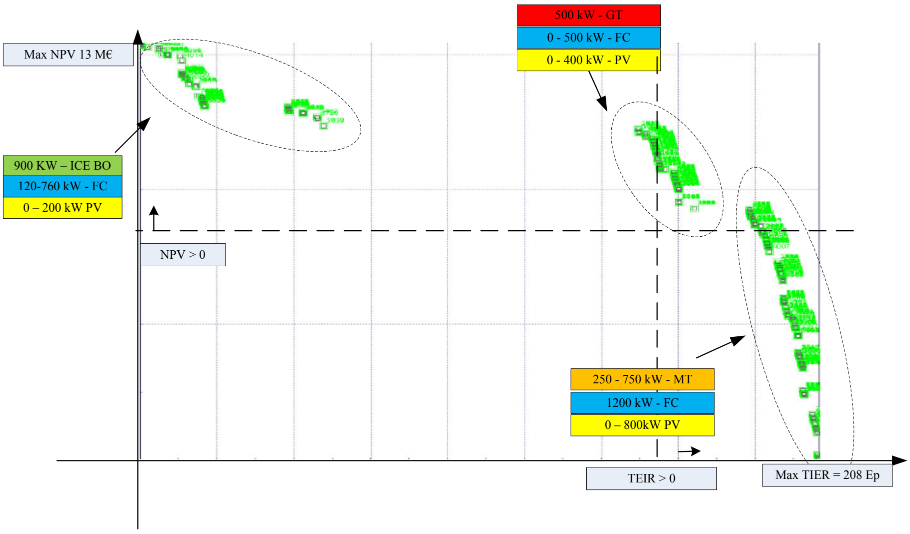

Figure 5.12: Pareto-Front for Multi-Objective plant design of Case Study, Scenario 2

The upper left part shifted downwards due to the increase in bio-oil costs, leading to a diminished NPV of about 13 M€. The optimization process seemed to be less accurate given that, as it was expected, the results for the right part of *Figure 5.12* should have been similar to the correspondent on *Figure 5.9*, while differences have been reported, as shown on *Figure 5.13*, to be compared to *Figure 5.10*. However, the accuracy of this step is left to be treated in the following paragraphs.

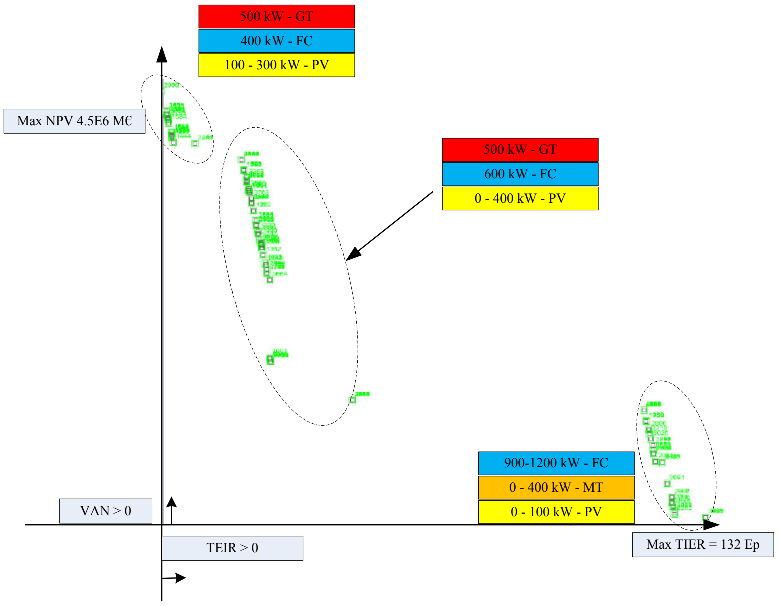

Figure 5.13: Pareto-Front for Multi-Objective plant design of Case Study, Scenario 2, details

5.2.2.3 *Scenario 3*

In the third scenario the simulation process accounts for the situation in which no-incentives have been taken into account. Such scenario provides useful information, given the variability of the benefit system. Results are shown on *Figure 5.14*.

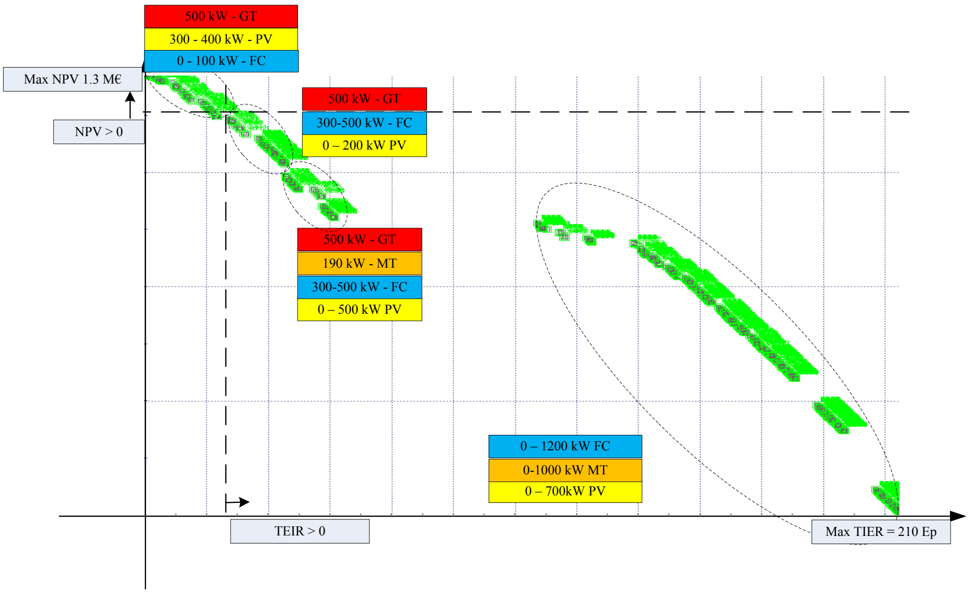

Figure 5.14: Pareto-Front for Multi-Objective plant design of Case Study, Scenario 3

The situation shown on Figure indicates that, without the current incentive system, no specific plant (or combination of plants) could provide both environmental while being contemporary economically beneficial, as shown by the empty upper-right quadrant. Economically viable solutions, however, have been found in combining a 500 kW_e Gas Turbine Plant (Thermal Power recoverable: about 1.5 MW) and a 300/400 kW_e Solar Panel, with the latter eventually substituted by a FC of lower sizes (about 100 kW) due to its higher power productivity.

5.2.2.4 *Scenario 4*

Eventually, the fourth scenario, considers both the nullification of incentives of scenario 3, but also an increase in heating and power loads, both subjected to a +25% modification. Results shown on Figure 5.15 are logically coherent with those of Scenario 3, considering the increase in plant potentiality, with some plant combination with positive redditivity including Micro-Turbines of limited size (max 200 kW).

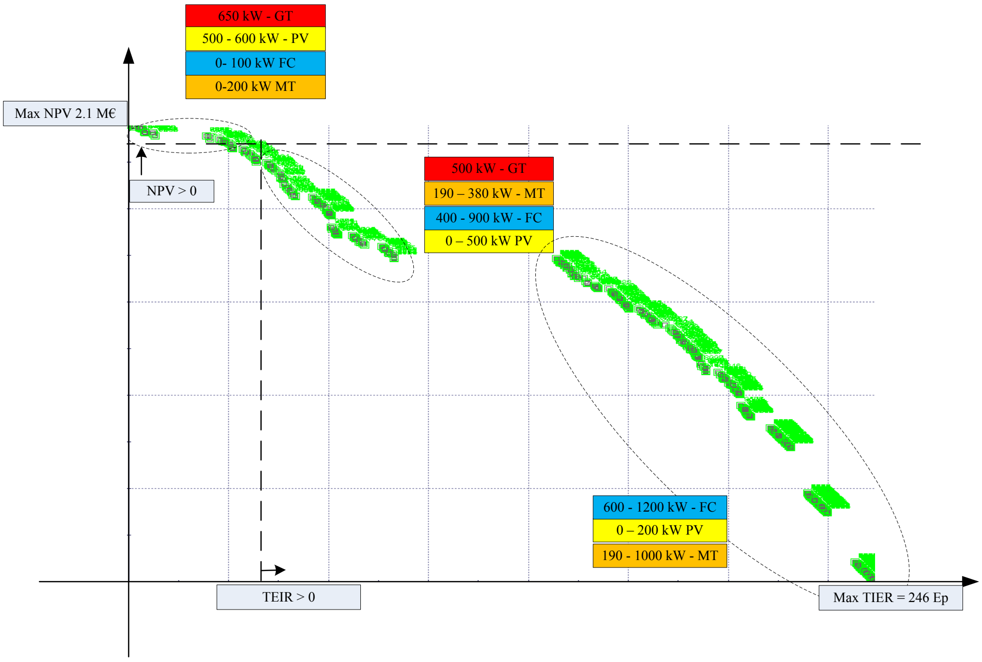

Figure 5.15: Pareto-Front for Multi-Objective plant design of Case Study, Scenario 4

5.2.2.5 Scenario 5

In this last scenario, the base case of Scenario 1 was modified by adding three constraints:

- NPV >0;
- TIER >0
- MAX_INV < 2.5 M€.

Such step was taken in order to provide a better view of the candidates solution proposed in the trade-off quadrant, providing both profitable and environmental friendly solutions. In order to provide more accuracy to the results, computational capacity has been increased, i.e. by increasing initial population (DOE = 100 designs) and scheduling time (350 generations), and, given the previous considerations, treating other plants (bio-oil and gas ICE) as constant value at zero capacity. Simulations were run for about 4 hours, while results are shown on Figure 5.16.

Results show that a range of alternatives is possible for having both economically viable solutions and emission-reducing plants. Interestingly, combinations of Gas Turbines, Fuel Cells, Micro-Turbines and PV were always considered in this range of solutions: in fact, increasing capacity of one of the plants for example, referring to the upper-left part of Figure 5.16, using, instead of 500 kW (GT) + 200 kW (FC) + 190kW (MT) + 100 kW (PV), a 900kW single Gas Turbines would have led surely to a reduced investment cost, but also an increase in wasted heat disposal costs (gas turbines provide an average 30-35% electric efficiency with higher heat surplus than FC's one) and would have led to a diminished NPV. Furthermore, emission rates of FC, PV and MT are less relevant than GT's ones, therefore it is possible that the single solution would not present a reduced environmental impact (TIER > 0) than the actual emissions.

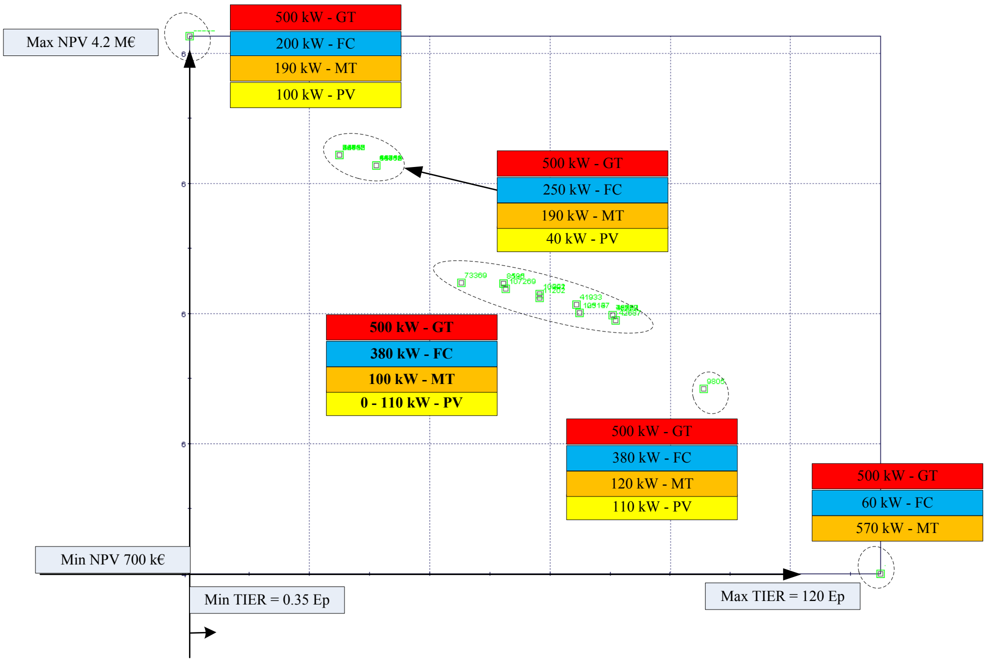

Figure 5.16: Pareto-Front for Multi-Objective plant design of Case Study, Scenario 5

5.2.3 Case study 2

The same MO model presented on chapter 3 has been applied to a smaller facility included in the sample, in order to evaluate the robustness of the model – and of CHP solutions - in a different framework, referring to the scale of facility's energy loads. Only the following scenarios have been considered:

- Scenario 1: base scenario, using current market-related economic parameters (fuel/electricity prices and trends, incentives value and trends) and most recent power/heat loads of the structure;
- Scenario 2: base scenario nullifying the contribution of national incentives on renewable energy or energy efficiency;

5.2.3.1 *Scenario 1*

The optimization model has been applied to the base scenario and the results are shown on Figure.

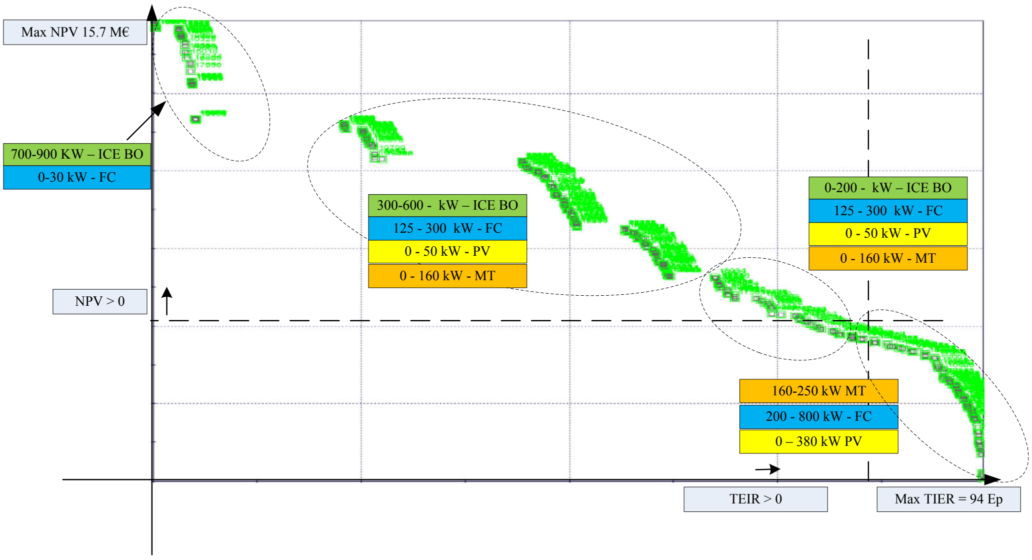

Figure 5.17:Pareto Front for Facility 2: Base Scenario

Similarly to the previous case, economic viability of bio-oil fuelled plants (the left part of the graph) makes such plants the most profitable solutions, often coupled with other kind of plants whose main driver is the electric efficiency of the system, confirmed by the presence of FC as second-best chosen technology. Shifting on the upper-right-side, no profitable and environmental-friendly solutions could be identified, with combinations of MT, FC and PV plants providing less impacting solutions but no-profitability.

5.2.3.1 *Scenario 2*

The assessment of scenario 2 (no incentives) for the considered facility is shown on Figure 5.18.

A peculiar situation is shown. No profitable solutions may be identified for the small-sized facility, and this was also expected due to impossibility of having economies of scale of large plant sizes and the absence of incentive system. However, on the top left part of the graph, bio-oil plants presents profitability still higher than gas-fuelled plants (which are featuring relevant gas prices at 0.7 €/nm^3), with, however, similar performances – in terms of profitability – of combinations of FC/MT/PV plants, which however presents better environmental performances.

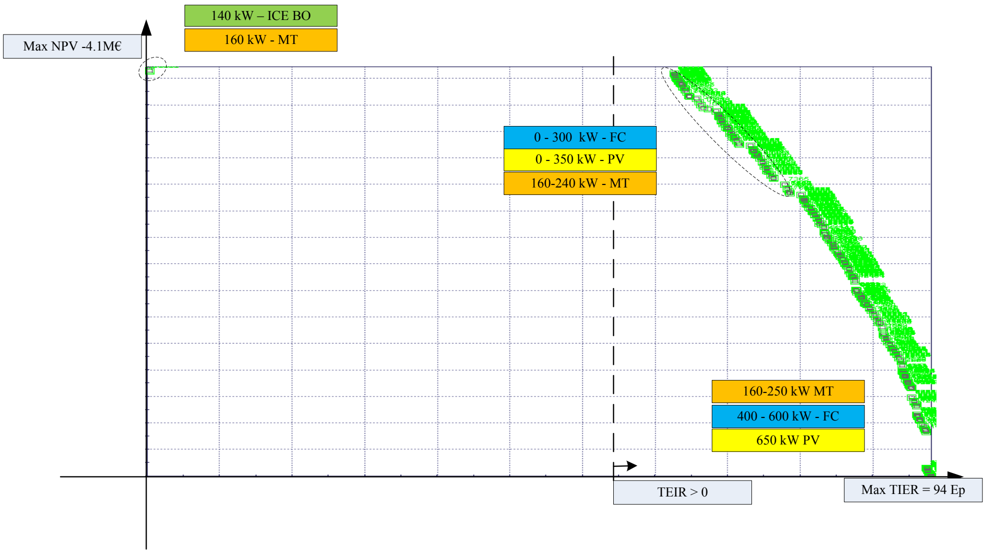

Figure 5.18:Pareto Front for Facility 2: No-Incentive Scenario

5.2.4 Regression Analysis on MO analysis results

The MO analysis, provided for the two sample facilities, has been used for the whole sample, considering the “no-incentive” scenario, aiming to provide generalized relationships for CHP plant design in the health-care industry. Of the total 21 facilities in the sample, fourteen provided completed data for MO assessment. The no-incentive scenario. Each simulation run took about 1.5 hours and appeared to be quite accurate when benchmarked to current installed capacities. However, two of the case studied would have required further scheduling for better optimization – especially considering that the design space assessed amounted for only the 0.5% of all the possible combinations – but at this stage it has been preferred to uniform the design space among the sample. The objective of the simulation has been that of identifying best performing solution (CHP type and size and PV peak capacity) from both the economic and environmental viewpoint, while contemporary assessing correlation among variables in order to provide insights for similar facilities in the health-care industry. NPV has been considered as the economic objective, while NOx emission has been used for environmental criteria.

Results are shown on Figure 5.19. A good correlation have been identified between CHP plant size and site-specific features such as power (Qe) and heat (Qh) loads, heated area and beds number, thus providing insights for cogeneration plant size estimation for health-care facilities.

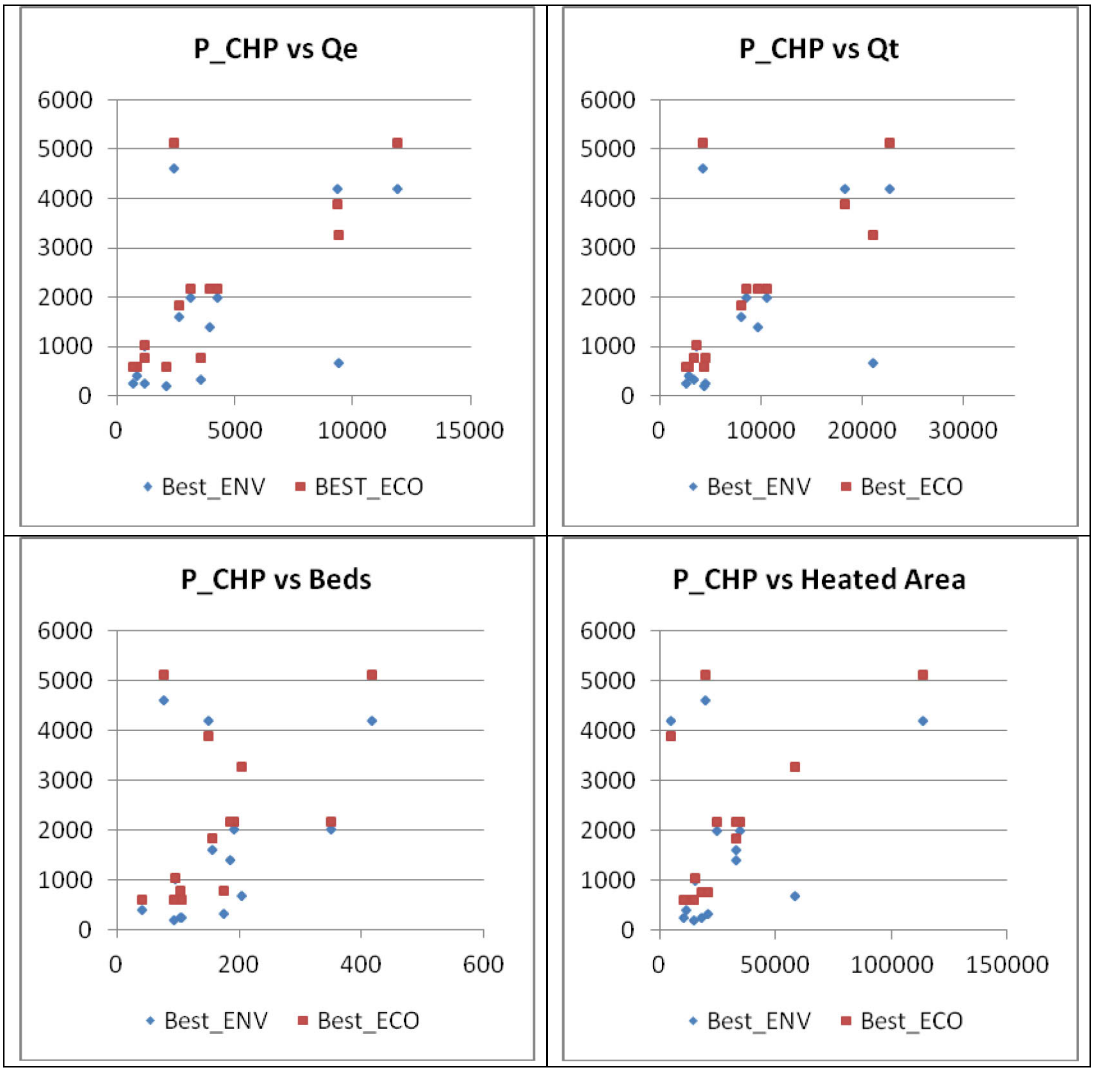

Figure 5.19: Regression analysis of MO results: Plant size (in kW$_e$) vs. Energy consumption (in MWh, power Qe and heating Qt), number of Beds, and Heated Area (m^2)

Internal Combustion Engines resulted as the most profitable performing solution for all the sampled companies, while Microturbines and Fuel Cells resulted as the least NOx-emitting installations, the former preferred for smaller plants (less than 1 MW). Performances of the simulated designs, depending of plants size and referred to economic profitability (NPV, expressed in M€) and environmental emissions (NOx, in t/year) are reported in Figure NUM and NUM respectively.

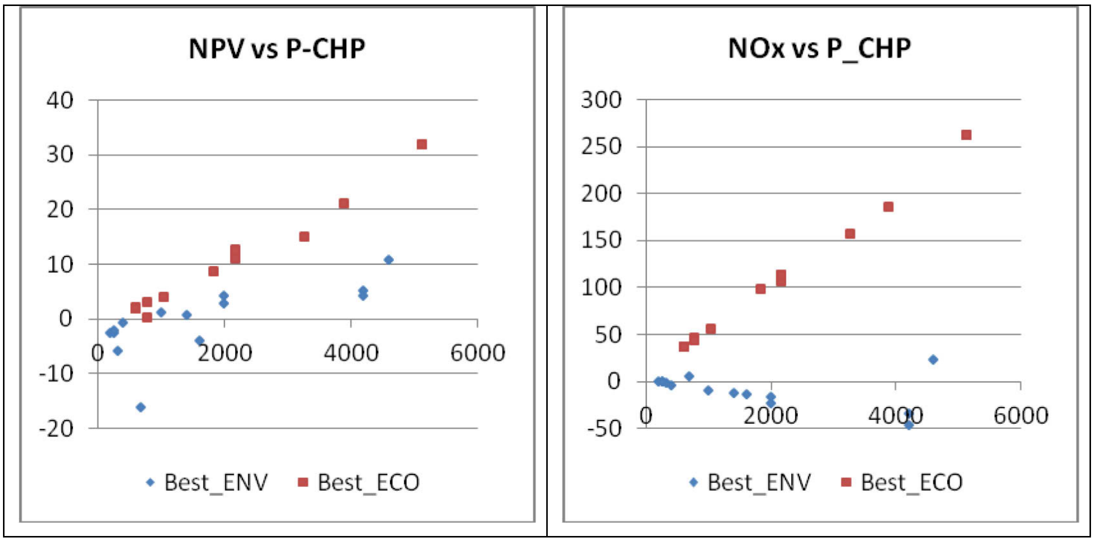

Figure 5.20: Regression analysis of MO results, economic (NPV, in M€) and environmental results (in tones of NOx emitted/saved)

The economic performances of ICE plants (Figure 5.20 a) resulted positive for all the case studies, showing great potential for the installation of such plants in the health-care industry, while profitability of best-environmental performing solutions has been found positive only for installations over about 1.5 MW_e. From the environmental viewpoint (Figure 5.20b), and considering stand-alone ICE's installations without abatement technologies, NOx production has always been superior to the emission avoided by heat and power savings, with linear trend. Fuel Cell and Micro-Turbines, combined with PV plant, compensate plant emissions by an increased amount of saved emissions, thus with a negative slope of the emission curve depending on plant size. Eventually, PV plant size results from the simulator have been studied. Considering this no-incentive scenario, PV plant in economic profitable solution sets has been found, for all the case studies, as zero. Best-Environmental solutions, for all the cases studied, included PV plants installed in roof-tops, but no trend/correlation could be found with PV peak capacity and structural data.

6

DSS for manufacturing

The project, financed by “CRUP fund” and commissioned by Unione Industriali di Pordenone (Industrial Chamber of Pordenone, Friuli Venezia Giulia, Italy), represents a “snapshot” of the energy and environmental management of some industrial companies in the Friuli Venezia Giulia region, particularly the Pordenone province, characterized by a relevant industrial presence particularly referring to small and medium size enterprises (SMEs). The project has been conducted from April 2009 to March 2010. Of the whole methodology, this project focused on the first two stages (the intelligence and the design stage), as shown on Figure 6.1.

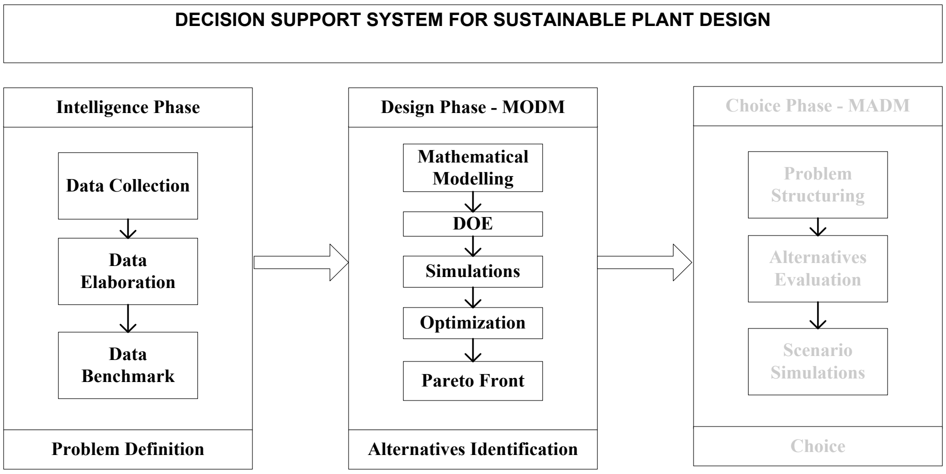

Figure 6.1:Methodological aspects treated in the section

Data collected during the first stage, by means of survey and walking-through audits, were elaborated in order to identify performance indicators (general or industry-specific), which have been later on benchmarked with internal and external sources. The details of the intelligence stage are assessed on section 6.1. Design stage, together with some other opportunities identified during the assessment, followed the mathematical model presented on chapter 6.2. Considering specific features of the industrial sector, the Multi-Objective design of CHP and PV plants has been studied, comparing results for various companies, as shown on section 6.3.

As a final deliverable, each of the sampled companies received a report assessing the results of the project, tailored on the specific data collected for the company itself, together with the possible opportunities to be implemented for improving firm’s sustainability. The following paragraphs present the results of the project on a general basis, avoiding, if possible, specific references to specific company’s activities.

6.1 Stage I: Data collection, elaboration and benchmark

The intelligence stage has been conducted in the three different moments of data collection, elaboration and benchmark. A preliminary stage of sample selection is also reported, in order to identify the main drivers for choosing the various companies to be included in the survey.

6.1.1 Sampled companies selection

Three main criteria have been used for selecting the companies among the associated firms of the Industrial Association of Pordenone, which commissioned the study, that is:

- Sectorial relevance: most of the companies belongs to the most relevant industries in the regional context, i.e. metal-working company (sector A), plastics working companies (B)

and wood/furniture industry (C), with a residual quota of other sectors companies (D).
- Absolute relevance in terms of energy (heating and power) loads;
- Territorial relevance, including the sample companies located at close distances (e.g. Industrial Parks)

Such indications had to cope with the effective needs of chosen companies, given the difficult economic framework and, at least for a large share of the sample, the low relevance of energy/environmental expenditure, at least when compared to the company's *core business*. Eventually, in the sample companies, those firms which demonstrate active interest towards the project have been included. The final sample is shown on the next figure.

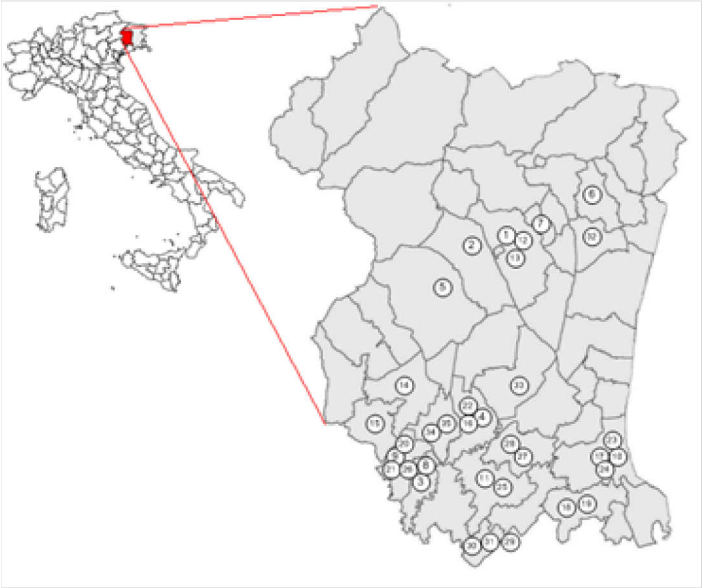

Figure 6.2: Sampled manufacturing companies in the project

6.1.2 Data collection

Preliminarily to the visits to the company's premises, a written survey has been sent to the company's personnel to be filled up, referring the last two full-year available data (2007/2008). The questionnaire consisted in five main sections, namely:

1. General information about the company: ATECO code[4], main business activity, revenues, employees, buildings' data (area and volume by function), hours worked, quality management and certifications systems, main clients and suppliers, market area, clients industry;
2. Qualitative and quantitative questions about the production cycle: cycle description, thermal treatments, heat recovery, automation, third-parties' activities, main machines installed;
3. Raw material, components and final products input/output flow analysis;

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[4] Equivalent to the NACE/NAICS code representing industry belonging

4. Qualitative and quantitative questions about energy and environmental management systems, such as recent works on buildings and equipment, diversified and periodical consumption monitoring, renewable energies exploitation, variable speed drives use, energy consumption and costs related to electricity, fossil fuels and other sources, divided, where possible, in ambient and processing consumption; water consumption (by source) and costs, water reclamation plant, waste production by type and destination, emission points and monitored pollutants;
5. Plant data collection, installed thermal/power and cooling potentialities (e.g. kW), year, operating temperatures, plant type, daily working hours, fuel, operating temperatures and pressures, maintenance costs; air emission abatements plants, by type.

The inspection of the company's premises (lasting about 2-3 hours) was conducted by means of walking through audit, as described on chapter 3. Such visit consisted in the following steps:

- Preliminary interview with the personnel responsible of filling up the questionnaire, in order to validate registered data and solving possible issues on some of the questions;
- Visits and assessment of the productive areas, following the productive cycle from raw material reception to final products storage, eventually interviewing specific personnel occupied in some of the most relevant stages of the cycle;
- Discussion with the personnel regarding company's priorities, opportunities and future/past projects in the energy and environmental field, and possible request of further data to elaborated for the final report.

6.1.2.1 Descriptive Statistics

A total 34[5] questionnaires have been received by the companies. The sample presents non-homogeneous features, regarding dimensions, industry belonging and productive cycles. In the following paragraphs some descriptive statistics will be provided.

6.1.2.1.1 General company's information

Among the surveyed companies, industry belonging is reported on Figure 6.3a. As shown, most of the companies belong to the metal-working industry (11 received questionnaires), wood/furniture (6) and plastic industry (6). A relevant quota of raw-material (4) and food industry (4) had been found. Residual quota is made up by companies in the textile, graphics and electronic field. Company's dimension, in terms of turnover, is shown on Figure 6.3b: most of the companies belongs to the category of Small and Medium Enterprises (with revenues inferior than 50 M€, whose 38% is a micro-enterprise, with turnover less than 10 million Euros, and 47% with revenues among 10 and 50 M€. About 6% of the sampled companies present higher turnovers, while for the residual quota (9%) no information could be gathered.

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[5] Some discrepances may be found among this number and the total number of observation in the following numbers. These differences may be attributed to separated companys structures (different buildings but same propriety) that, when available, have been treated separately.

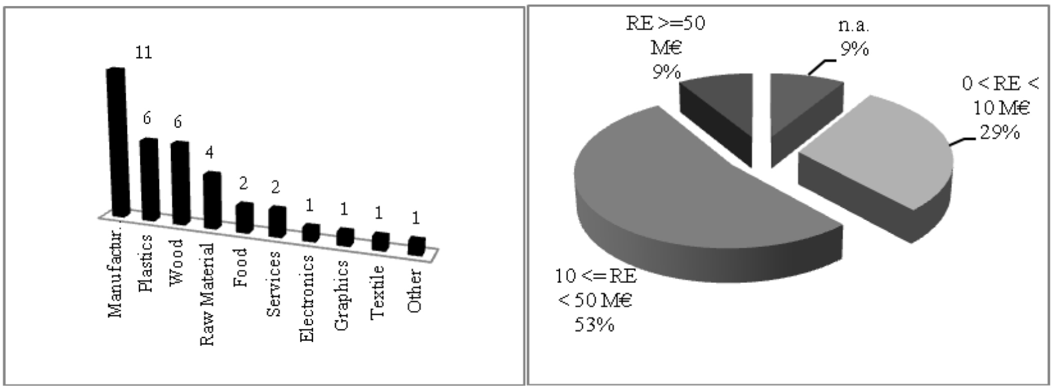

Figure 6.3a and b:Descriptive statistics, industry and size

Also the classification of sampled companies depending on employees number presents a similar structure, with prevailing small/medium size companies with employee number below 250 (82% of total sample, whose 17% between 0 and 50 and 65% between 50 and 250)as shown on Figure 6.4a. Eventually, referring to companies' certification and managements systems (Figure 6.4b), about two thirds (65%) of sampled companies presents the ISO 9001 – 9003 standards, and a relevant quota gained the ISO 14001 (56%) standard. Still few companies' presents the voluntary EMAS regulation (3%), often complemented and substituted by industry-specific certifications.

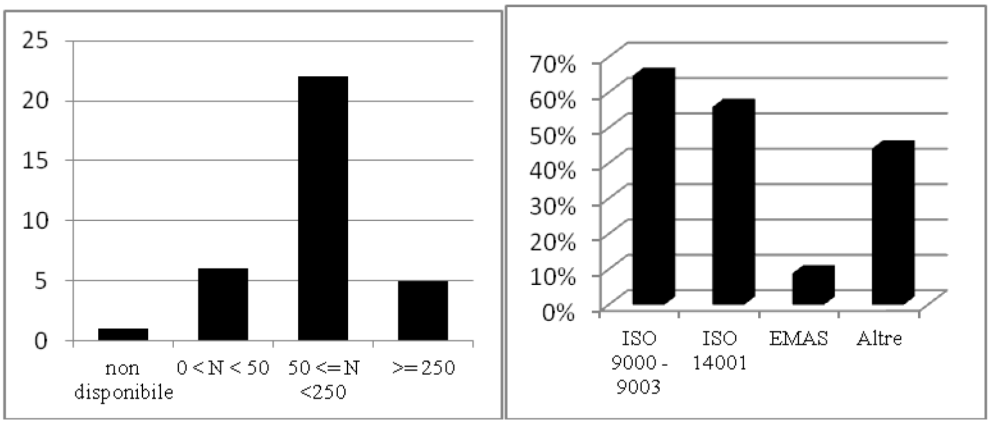

Figure 6.4a and b:Descriptive statistics, employees and certifications and size

6.1.2.1.2Qualitative and quantitative energy data

Among the information gathered in the written survey filled up by company's personnel, the relevance of energy/environmental costs, in terms of percentage of related expenditure (waste/water treatment, energy supply, etc), is less than 10% of total turnover for more than 65% of the companies, as shown on Figure 6.5. The expenditure, therefore, is less relevant when compared to the other company's costs (e.g. raw material, personnel, etc.) for most of the sample. About 12% of the sample presents higher percentages, even if some of the companies couldn't respond to the question. Sample differentiation is also shown by the various productive cycles, which, for the purposes of the research, have been classified in terms of heating treatments to the input materials. The following heat processes have been identified:

- High temperature (> 350°C)[6];
- Medium temperature (between 100 e 350°C)
- Low temperature (< 100°C)
- No relevants heat treatments.

The division of sampled companies related to this last classification is shown on Figure 6.5b, showing an almost equal division among the four categories identified.

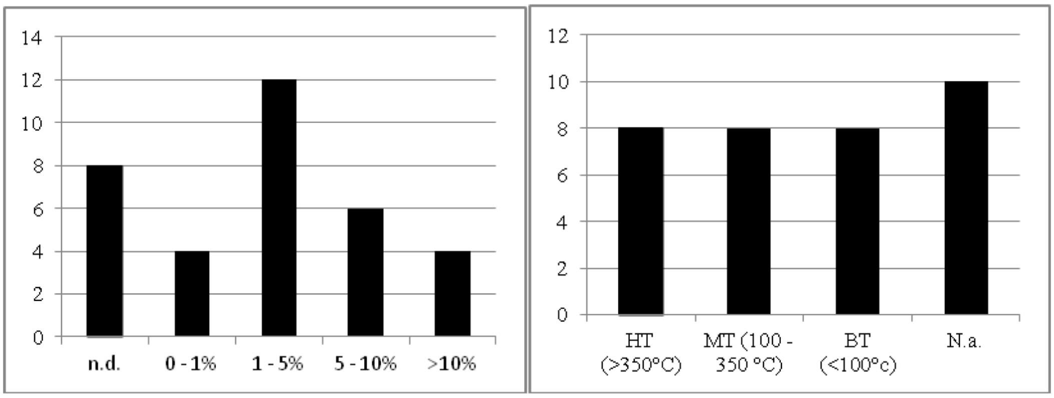

Figure 6.5a and b:Descriptive statistics: percentage relevance of energy/environmental expenditures and heat treatments

Referring to productive cycles' power consumption, a classification of the sampled companies has also been assessed (graph not shown). For most of the sample (77%), the automation level is considered by the personnell as "high" or "medium/high", while productive cycle is addressed as the most important energy consumer, as registered in a a specific question in the survey. Eventually, some of the answers related to the presence of an Energy Manager, differentiated meterings of energy consumption, utilization of CHP plants or renewable-fuelled plants are shown Figure 6.6.

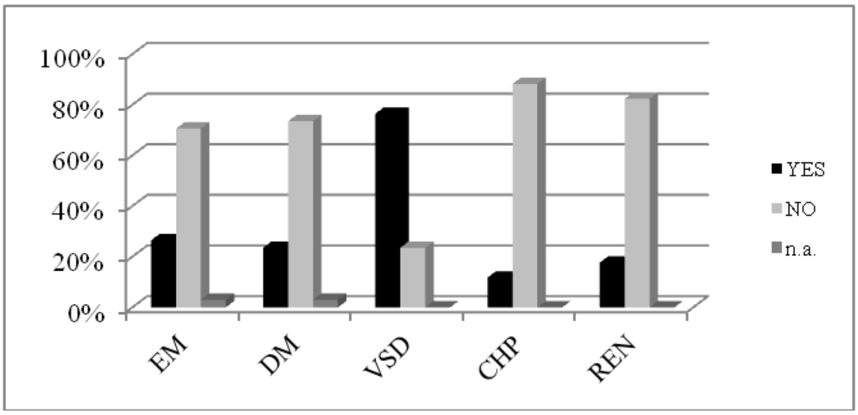

Figure 6.6:Descriptive statistics, responses on some of the qualitative questions

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[6] In this category also the companies with low temperature (<0) have been considered.

6.1.2.2 Statistical Analysis: correlation analysis

Some of the data gathered from the previous stage have been correlated among each other in order to identify trends and correlations among sampled companies. The goals of this stage are multiple, such as:

- From the organizational/planning level, it is possible to estimate the value (present or future) of some parameters as a function of others (energy consumption depending on expected turnover or employees' number);
- From an industry level, the identification of sectorial-trend allow to both companies and industrial association to identify and monitor effective benchmark indicators, representative of the considered industry;
- From a company perspective, it allows to positionate the company comparing its performances to internal or external trends and thus determining areas to be assessed;

Given the broadness of the sampled company, it has been considered appropriate to limit this statistical assessment to the most representative sector among the sampled companies that is the metal-working industry.

6.1.2.2.1 Correlation assessment in the metal-working industry

Firstly (Figure 6.7) the correlation between energy consumption and turnover has been considered (left-side). The correlation value (R^2), apparently low, is significantly higher (right side) due to the exclusion of a particularly relevant company, highly differing by size and turnover by the others. Excluding such company, the correlation between total energy consumption (summing up power and heating consumption) and company's turnover is very high, and the regression relation might be used for forecasting energy consumption depending on expected turnover trend.

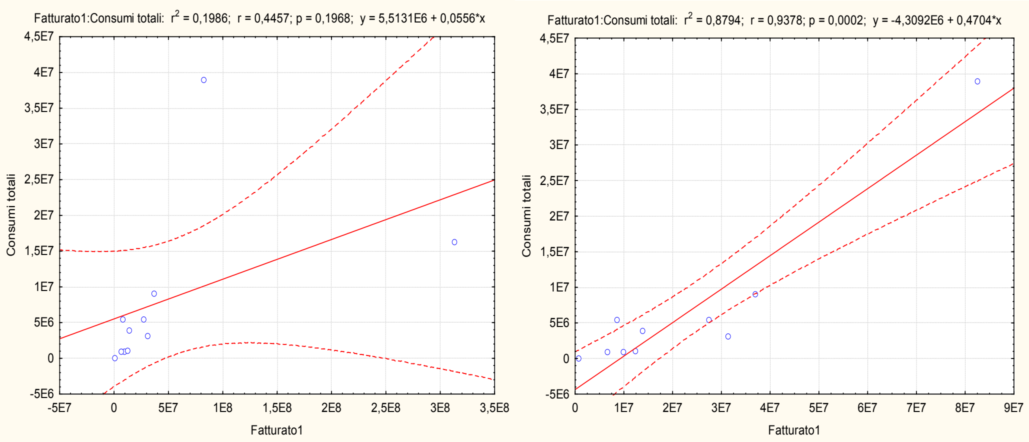

Figure 6.7: Manufacturing industry: correlation analysis between total energy consumption and turnover

Similarly, the correlation between power consumption and turnover (Figure 6.8), apparently low (left-side Figure), presents relevant values when excluding the previously-cited company (right side).

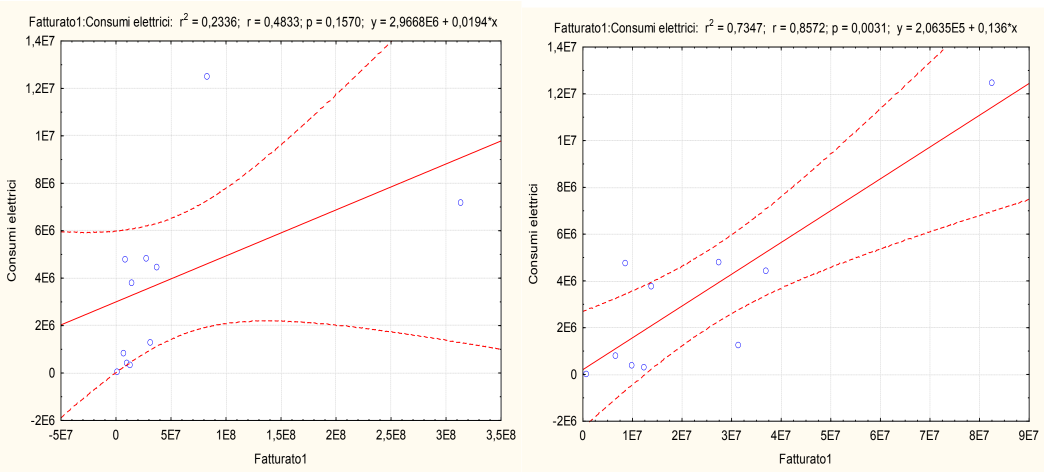

Figure 6.8: Manufacturing industry: correlation analysis between power consumption and turnover

Correlation between heated area and thermal consumption (Figure 6.9), has also to be "cleaned" by a company presenting relevant productive cycle heating consumption. Correlation analysis on the right side of Figure 6.9 shows particularly high correlation values.

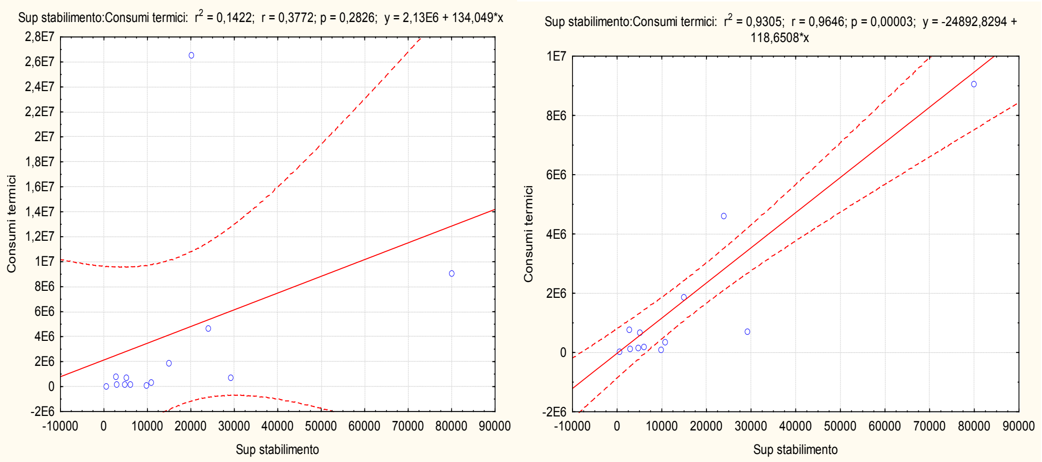

Figure 6.9: Manufacturing industry: correlation analysis between heat consumption and surface area

Correlation between employee number and turnover (Figure 6.10) is very high both considering total employee number (left side) and "blue-collars" employee only. The regression relationship may allow calculating variations in employment due to expected variations in company's turnover.

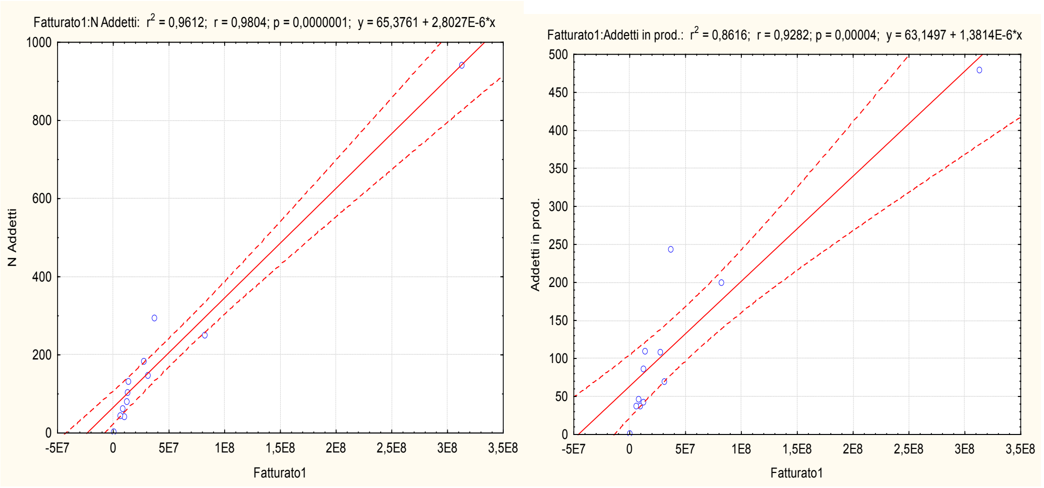

Figure 6.10: Manufacturing industry: correlation analysis between employee number and turnover

The correlation between water and energy consumption (Figure 6.11) is not relevant when all the sampled companies in the metal working industry are considered (left side). Such correlation, however, grows significantly when excluding a company which features high water usage for process uses. (right side).

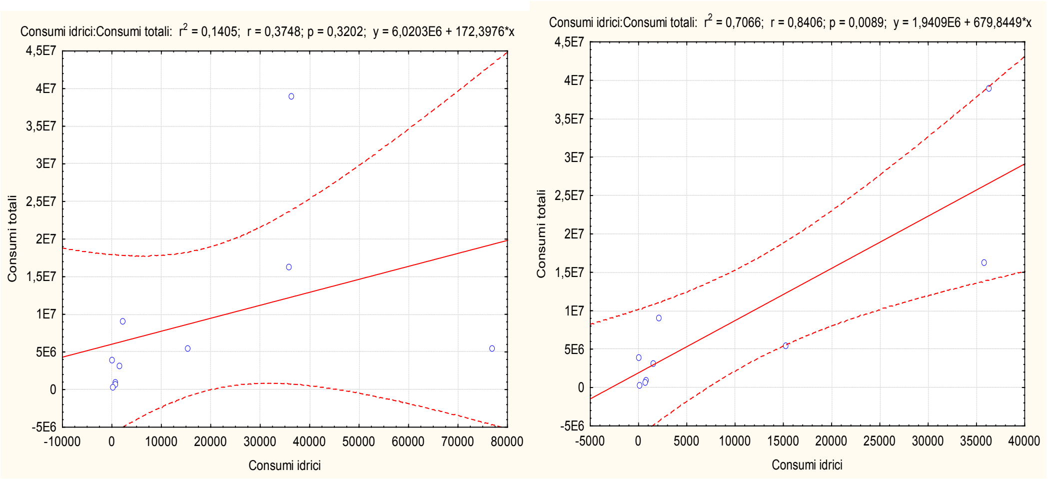

Figure 6.11: Manufacturing industry: correlation analysis between water and energy consumption

Eventually, the correlation between total worked hours and turnover (Figure 6.12) is moderate, especially when excluding the case of the large manufacturing/assembler company considered at the beginning of the paragraph and shown on the right side of Figure 6.12.

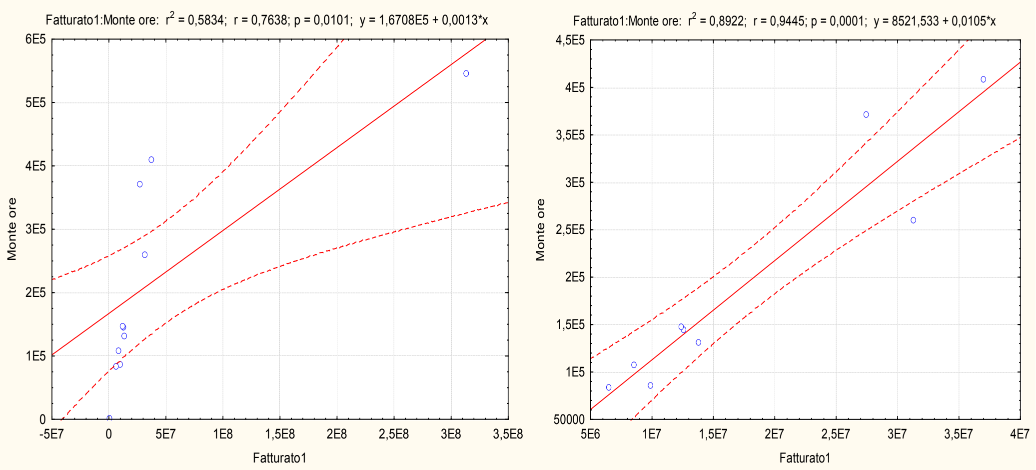

Figure 6.12: Manufacturing industry: correlation analysis between turnover and worked hours

6.1.3 Data elaboration

The second step of the "Intelligence Phase" consists in qualitative and quantitative, which have been elaborated in order to provide descriptive statistics of the sampled group of companies and together identifying, assessing and benchmarking performance indicators.

6.1.3.1 Performance indicator

The various data collected refers to three main areas, i.e.:

- Organizational/Administrative data, such as turnover, employees, worked hours, shifts, etc.;
- Plant/Facility data such as heated area/volume, installed capacities (heat, cooling and power);
- Consumption data, related to heat, power and water consumption, and waste production.

Indicators related to such areas will be calculated in the following paragraphs.

6.1.3.1.1Indicators identification

Indicators for internal (among the sampled companies) and external (with similar companies outside the sample) benchmark have been calculated from gathered data. Such tool, as reported on chapter 3, represents a useful tool for monitor company's performances.

Specifically, the following indicators have been calculated:

- Ratio between power and heating consumption, both expressed with the same unit of measurement, and defined "electric index", characterizing the structure of company's loads;
- The ratio between total energy consumption and company's turnover, defined as the energy intensity of the business, and expressed in kWh (or equivalent) per euro, identifying those companies with particularly energy intensive activities;
- Ratio between energy consumption and total employee, indicator of pro-capita energy consumption, and indirectly of company's automation;
- Similarly to the previous indicator, the ratio between total consumption and personnel employed in productive activities;

- The ratio between production-employed personnel and total employees, indicator with similar relevance of the last two ones;
- The ratio between total energy consumption and worked hours, indicator of energy intensity of company’s business;
- Ratio between water consumption and turnover, index of the utilization intensity of water related to company’s business;
- Ratio water consumption and energy consumption, indicator of the intensity of water usage compared to the energy demand.

6.1.3.1.2Indicator approach: internal benchmark

Internal benchmark, in terms of occurrence frequency (i.e. number of observations) among the sampled companies is shown on Table 6.1, together with a brief comment on distribution trends.

Table 6.1: Indicator for the sampled companies: distribution

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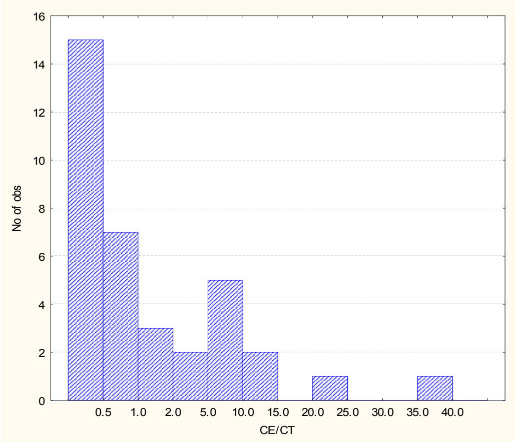

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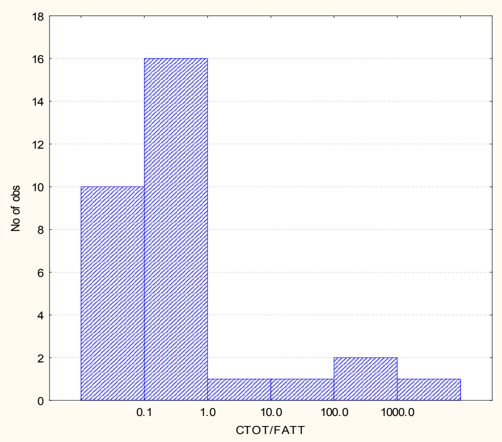

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<tr>
<td>Power/Heating Loads: a relevant quota of companies presents a higher heating consumption compared with power ones.</td>
<td>Total Energy Consumption/Turnover (kWh/€): most of the companies presents a ratio inferior to the unity value.</td>
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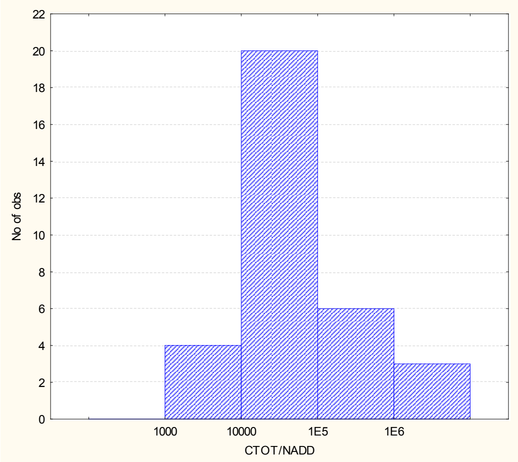

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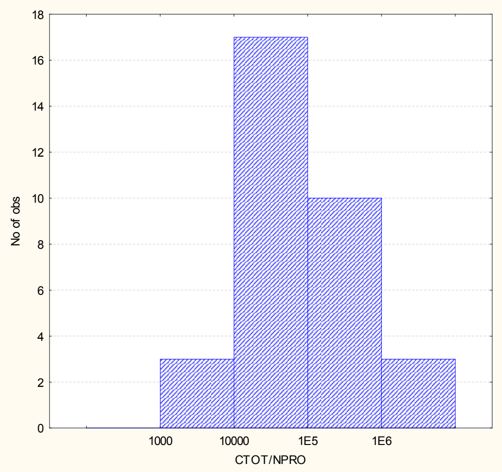

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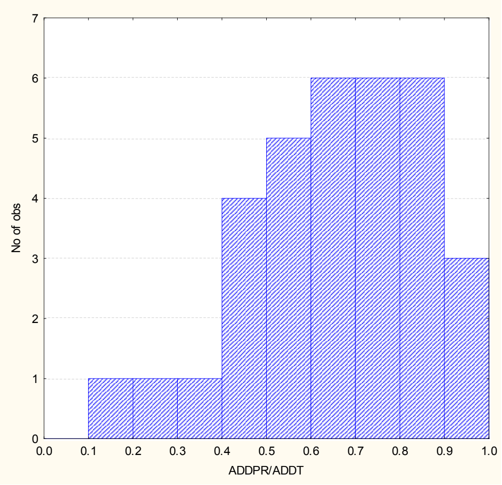
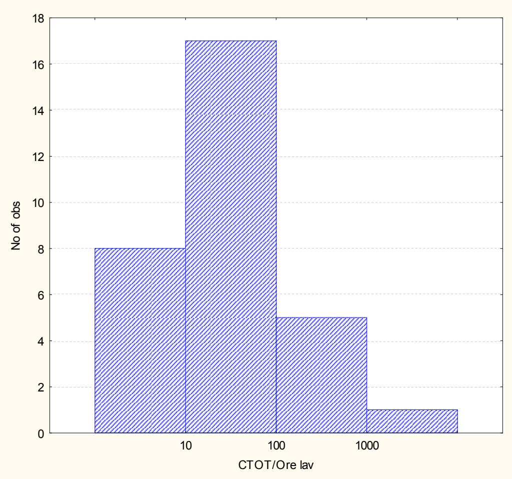
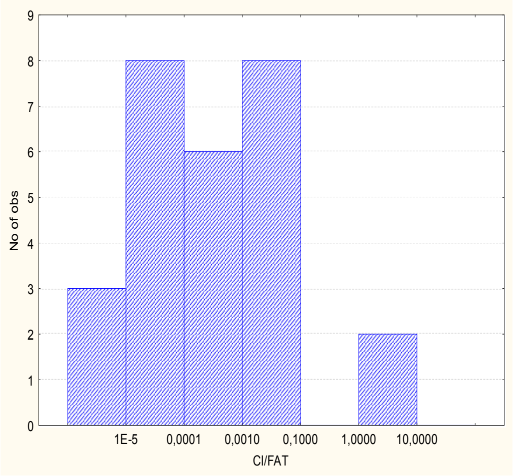
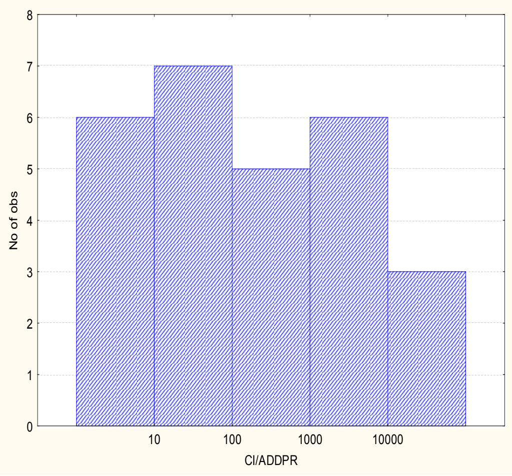
Energy consumption per total employees (kWh/emp): most of the companies presents n average consumption between 10.000 e 100.000 kWh/emp, with a prevalence, inside this broad range, of values between 10.000 e 50.000 kWh/emp.	**Energy consumption per production employees (kWh/emp_p)**: similarly to the previous graph, with prevailing indicator with pro-capita consumption between 10.000 e 100.000 kWh/emp_p
	
Production/total employee (%): most of the sampled companies presents an a relevant productive structure, with more than 50% of the total employees occupied in productive activities	**Total energy consumption per worked hours (kWh/h)**: most of the companies presented an average value between 10 and 100 kWh per worked hour
	
Water consumption per turnover (m3/€) :most of the companies presented a water intensity indicator less than 0.1 m3/€, with no defined distribution to be identified.	**Water consumption per productive employee (m3/add_pr)**: also in this case the distribution of pro-capita water consumption is scattered and no specific trend may be

	identified.

6.1.3.2 Indicators for external benchmark

The indicators previously calculated are useful for descriptive statistics of the sample, but does not provide useful information to the company whether the latter are over- or under-performing with respect to similar companies or industry standards. For this reason, some other company- or industry-specific indicators have been calculated and benchmarked to similar internal or external references.

For example, considering the injection molding industry and the treatment of thermoplastics polymers, a specific energy consumption indicator has been considered, i.e. the electric usage per kg of plastic material input (Figure 6.13). Such value has been calculated for the companies in the sample, together with the data of a similar, more comprehensive study, conducted on the plastic industry of the same province. This process allowed to identify to preliminary identify best performing companies while together providing some insights to firms with higher specific energy consumption.

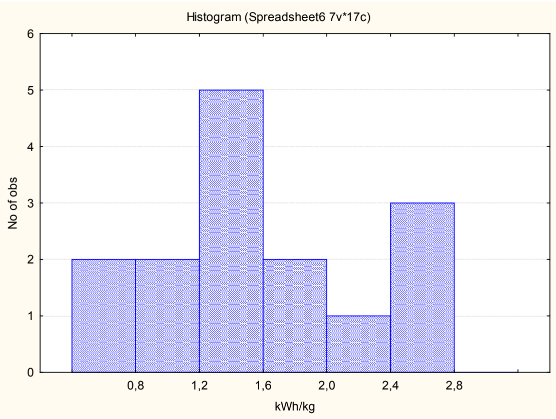


Figure 6.13: Specific energy consumption of thermoplasts injection molding

Similarly, clinker production process has been assessed. The theoretical specific consumption value, considering only process energy requirements of chemical reactions - has been quantified in 1.7 GJ per ton of clinker produced (IPCC, 2011). Such value has been compared with the calculated values of two companies in the sample. This theoretical value, however, represents the lowest bound, with more realistic energy consumption for wet-cycles at 5 GJ/t and 3/3.5 GJ/t, for dry-based clinker processes. However, given that about 50% of energy consumed is wasted in the productive cycles, leaving much room for energy savings opportunities which will be assessed later on.

$$\eta = \frac{(GJ / t_{cl})_{theoretical}}{(GJ / t_{cl})_{company}}$$

Glass production of one of the company in the sample, the specific energy consumption of the company was compared to the information provided by the related IPCC's BREF on glass production (IPCC, 2011). Thermal and electric energy indicators have been calculated. Relating to the former, values obtained have been compared to data collected from the BREF, which reports a range varying from 10 to 17 GJ/t. Also water consumption amounting to have been compared to specific figures of the EU reference document, which reports a specific water usage of 1.7 – 2.9 cubic meters per ton of glass. Comparisons of company's indicators are not shown due to confidentiality reason, but allowed to provide an external benchmark for company's use.

6.2 Stage II: Design Stage

After having thoroughly assessed company's data and benchmarked it with similar company's or literature references, opportunities for improving company's performances are shown on the following paragraphs. This step relates to some specific opportunities which have been studied for single companies or for co-localized group of companies. Eventually, the application of the mathematical model described on chapter 3 will be applied to some of the companies in the sample.

6.2.1 Specific company's opportunities

As previously described, qualitative and quantitative data were collected by means of the questionnaire and the visual inspection of the firm's buildings allowed identifying some of the opportunities for reducing energy consumption and costs.

This stage of the survey was conducted with the dual aim of identifying opportunities for:

- Single companies, where the solution was specifically tailored to the actual needs of a single firm, or homogenous industries, identifying solutions for similar productive cycles (e.g. thermo-plastic injection molding). This type of solution involves only the commitment of a single company.
- Territorial contexts, characterized by co-located industries, or homogenous networks of industries (e.g. the local furniture district), involving the commitment not just of more than one company, but also of institution, regulators and other public/private stakeholders.

6.2.1.1 Opportunities for single companies and homogenous industries.

Most relevant single-firm opportunities were related to energy intensive industries (e.g. cement works), large companies or particularly suitable industries (e.g. plastic injection molding) and are reported hereafter.

- Because of the relevant amount of hot flue gases coming out of the chimney of a metallurgic company, a techno-economic evaluation of a recovery plant using Phase Changing Material (PCM) in a company producing pig-iron was studied. The thermal heat recovered would be coupled to a low-grade heat-to-power converter (ORC);
- In two plants producing clinker (the hydraulic binder of cement) the opportunity of insulating the 60-meter rotary kiln, because of the significant losses during this stage, has been studied, together with the energy recovery from the hot flue gases;
- In a dairy company, given the complementarities of electrical and thermal energy needs, the opportunity of installing a CHP plant has been studied. This solution would allow the self-production of power (of the various motors and cooling plants) and thermal needs (of the pasteurizing and the clearing-in-place processes);
- In the plastic processing industry, most of the surveyed companies presented a similar productive cycle, involving the injection molding of thermoplastic polymers. For such industries, the possible substitution of the hydraulic-driven presses with all-electric ones

could substantially reduce the amount of electricity consumed, as reported in literature references and manufacturers specification.

- Eventually, generic information referred to lighting equipment, electric motors, compressed air systems, and plants for the self-production of electricity singularly (photovoltaic plants), or in a combined way (CHP plant), were given for some of the firms which were evaluated suitable for such opportunities.

Some of the quantitative data computed for the above solutions are reported on Table 6.2

Table 6.2: Main opportunities identified for single companies or heterogeneous industries.

Industry	Opportunity	Main Features
Cement-Work	Heat recovery from flue gases	Flue gases out at 350 °C, recoverable with power production by means an ORC plant
Cement-Work	Rotary kiln insulation;	Estimated 3-4% saved through mineral wool kiln insulation
Metallurgy	Heat recovery from flue gases	30.000 Nm^3 at 700 °C recoverable, use of PCMs for thermal fluctuations' reduction and power production by means of a 500 kWe ORC plant
Dairy	CHP plant	Estimated plant power: 750 kWe, using natural gas. Estimated savings: 250 k€/y Payback: 3-4 y
Injection Molding	All-electric press	Energy savings up to 70% depending on cycle-time, estimated 20% investment additional costs.
Various	Photovoltaic plants	Ranging from 5 peak kW to 100 peak kW, depending on companies' needs
Various	Lighting equipment	Compact fluorescent, LED and sodium-vapor lighting equipment, depending on energy efficiency, Color Rendering Index (CRI), Coordinated Color Temperature (CCT)
Various	Electric motors, Compressed Air	Correct maintenance, avoiding over-sizing, load factor monitoring. Heat recovery from compressors (up to 80% of the total input), estimating and finding leakages in the distribution systems by sonic detectors.

6.2.1.2 Territorial opportunities

Territorial opportunities, involving co-located companies or networks, have also been identified. Such opportunities, anyway, have to be deepened considering both the many actors and stakeholders involved in the decision-making process, and a more detailed quantitative evaluation of availabilities and needs.

First territorial opportunity refers to the furniture industry – to which six sampled companies belongs – distinctive sector of the whole region and particularly in the Pordenone province, and to the two cement-works in the sample. Uncontaminated waste wood produced in the former is commonly used in chip-board production and therefore re-used in the productive cycles. The variability of chip-board production firms' wood demand, together with the presence of contaminated wastes (e.g. by solvents) led to the need of disposing of a considerable amount (estimated 50.000 ton for the whole province) of such waste. The use of such relevant amount inside the extremely energy intensive productive cycle of clinker could lead to a win-win solutions for both actors considered.

The second identified opportunity refers to an industrial area in which four of the sampled companies are currently located. The whole industrial park consists of about 120 companies, each one taking electricity and fossil fuel (mainly natural gas) from a common park's infrastructure. It's the authors' opinion that industrial parks – and especially for those featuring a main directional centre and an environmental management system as ISO 14001 – should shift from the materialistic view of industrial ecologies concepts to a 'common energy production' perspective. In particular, the contemporary presence of thermal, power and cooling demands could lead to a balanced Combined Heating, Power and Cooling (CCHP) central plant, centrally managed and specifically sized. The development of a specific supply chain for renewable fuels would be the next stage for reaching what the authors names an ‘Energy Autonomous Eco-Industrial Park’ (EAEIP). This solution, anyway, has to deal with technical issues about variable demands and infrastructure development and should be implemented gradually, but could represent a significant benefit for the whole area, economically and environmentally. Some of the main technical features of the two systemic solutions are reported in Table 6.3.

Table 6.3: Identified system-wide opportunities: reference industry, synergies and main features

Name	What	Description
Cement-Work, Furniture	Wood waste treatment	Depending on chip-board demand, about 50.000 tons of wood waste in need to be disposed of. Wood homogenization, needed for efficient combustion inside rotary kiln, would be achieved through tube drying, a 6t/h hammer mill for waste pulverization and a 3 t/h pellettizer. Estimated investment costs: 2 – 2.5 M€, operating cost: 1 – 1.5 M€. Kiln burner modification was not considered.
Energy Autonomous Eco-Industrial Park (EAEIP)	Complementary cooling, heating and power needs; renewable fuel chain to be developed.	Estimated base load thermal input needed for cooling (by means of absorbing equipment) and partial space heating: 5.000.000 kWh. Chosen technology: Reciprocating Engine. *Solution a)* Natural gas as fuel: power output 6,3 MW_e (7 MW_{th}). Estimated investment costs: 8 – 9 M€. Cash flows: 1-1.5 M€/y. Payback:7-8 years. *Solution b)* Bio-oil as fuel. power output 8,3 MW_e (9,2 MW_{th}). Estimated investment costs: 15 – 16 M€. Cash flows: 5-6 M€/y. Payback:3-4 years. Financing and contracting forms to be investigated.

6.3 Multi-Objective analysis

Having reviewed the sampled companies, the multi-objective model which has been structured on chapter 3 has been applied. The preliminary step to the optimization process referred to the following parameters selection:

- **Initial DOE**: in order to define the initial candidate solutions to be assessed by the optimizer, it was chosen, for easing the scheduler, to manually add an initial set of candidates (five solutions) which are feasible (non constraints broken); the other candidates of solutions have been chosen by using the Incremental Space Filter (ISF) algorhytms, as introduced on chapter 3;
- **Scheduler**: Non-Selective Genetic Algorhytms (NSGA –II) has been as the optimization algorhytms chosen. Such scheduler, compared to other optimizer tested during the simulations, proved to be extremely powerful because of the intrinsic, elitists, properties and the capacity of adapting the scheduler options to the pareto front movements;
- **Simulator parameters**: a broad range of optimization parameters could have been chosen at this stage. However, the following scenarios have been considered:
    - Scenario 1: base scenario, using current market-related economic parameters (fuel/electricity prices and trends, incentives value and trends) and most recent power/heat loads of the structure;

- Scenario 2: base scenario nullifying the contribution of national incentives on renewable energy or energy efficiency;

The model has been applied to two different companies of the sampled group, differing by consumption structure and loads, working hours and productive activity. Specifically, the following case studies have been considered:

- A medium-size manufacturing company, whose primary energy consumption is related to power loads while heat loads are required only for winter heating. The company works in 24x7 shift;
- A small-size manufacturing company, whose energy loads are similarly distributed among heat and power consumption, daily working on a single shifts;
- A medium size manufacturing, with similar heating and power loads. Heating loads are to be used for both low (60°C) and medium-high (100-120°C) temperature process uses.

Without providing the name of the company for confidentiality reasons, the broad consumption data are reported on Table 6.4

Table 6.4: Main data on the companies considered in the case study

	UM	Company 1	Company 2	Company 3
Shifts	#	3	1	2
Power Loads	MWh	4800 MWh	308 MWh	4885 MWh
Heat Loads	MWh	675 MWh	785 MWh	8484 MWh
Ratio		7.1	0.39	0.57

6.3.1 Scenario 1

The application of the multi-objective model to the Company 1, featuring a large difference between power and heat consumption, is shown on Figure 6.14.

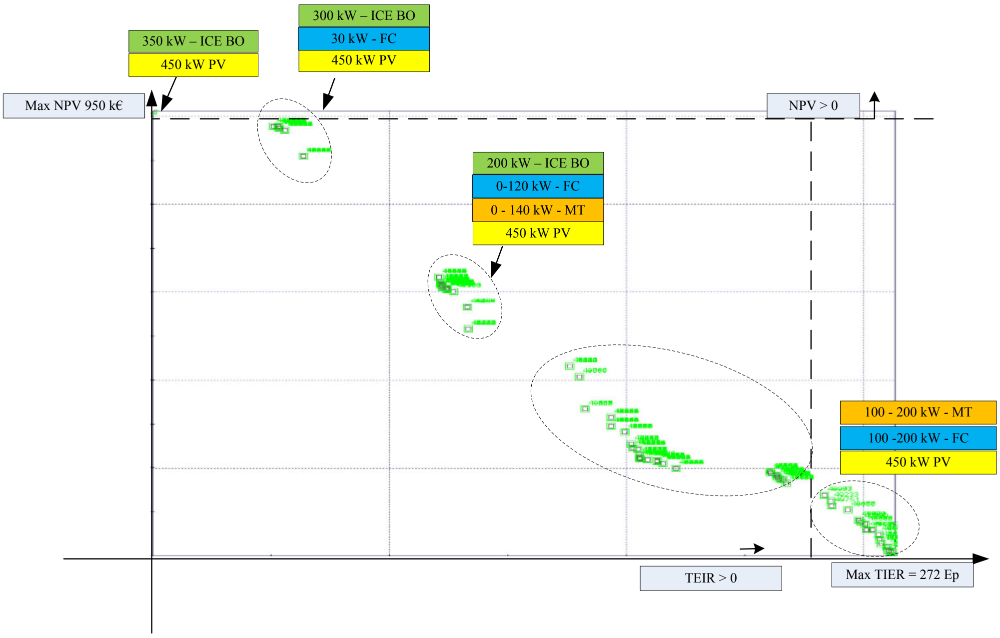


Figure 6.14: Pareto front for Company 1, Scenario 1

Power Installed, for partially satisfying company's needs, while respecting the constraints previously described, is equal to 750 kW, with different combinations for different profitability and environmental impacts. The figure shows that a combination of Bio-Oil CHP (350 kW) engine a 450 KW PV plant could partially satisfy company's needs (60% of Power Needs, data not shown), but its economic viability would strongly depend on incentives and low bio-oil prices. Going down from the Pareto front top-left solutions, on the quadrant with negative NPV and TEIR, a range of solutions still featuring profitable bio-oil plant, combined with FC and MT solutions, and all of them featuring a relevant PV plant (about 450 kW), associated to the large power requirements as previously described. Eventually, on the lower-right part of NUM solutions combining PV, MT and PV provide the largest environmental benefit, despite the clear disadvantages in terms of profitability. Regarding Company 2, the situation is very different and it's shown on Figure 6.15.

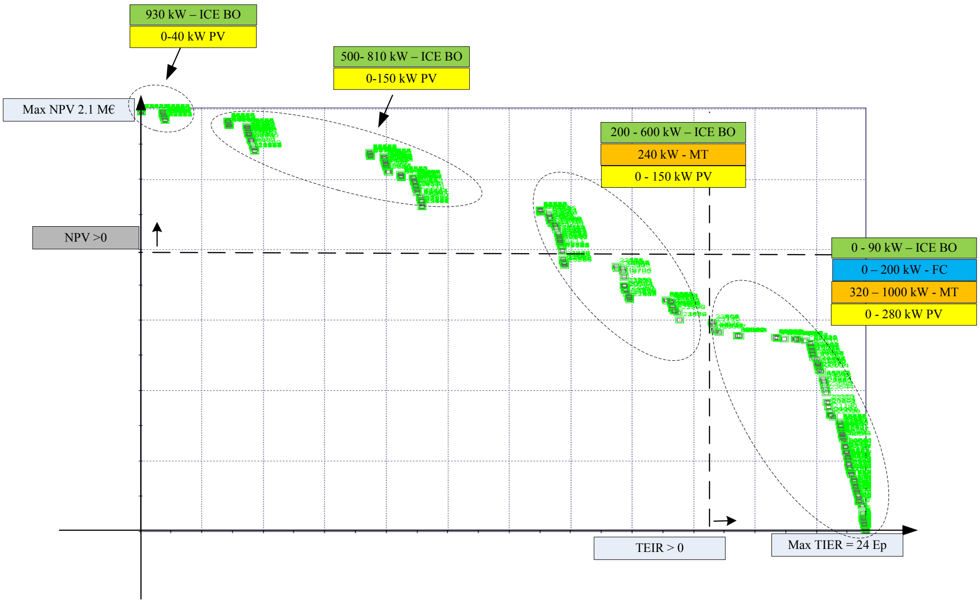


Figure 6.15: Pareto front for Company 2, Scenario 1

A range of alternatives providing profitable solutions, however still relying on highly incentified bio-oil and PV plants, allowing satisfying company's demand (1MW power installed, about 1.5 MWt heat capacity). No solutions allows to both satisfy economic and environmental benefits (NPV >0 and TIER >0, upper-right quadrant) while a range of combination of Micro-Turbines and PV plant, eventually associated with FC, accomplishes the most relevant environmental performances.

Eventually, solutions for Company 3 are shown on Figure 6.16

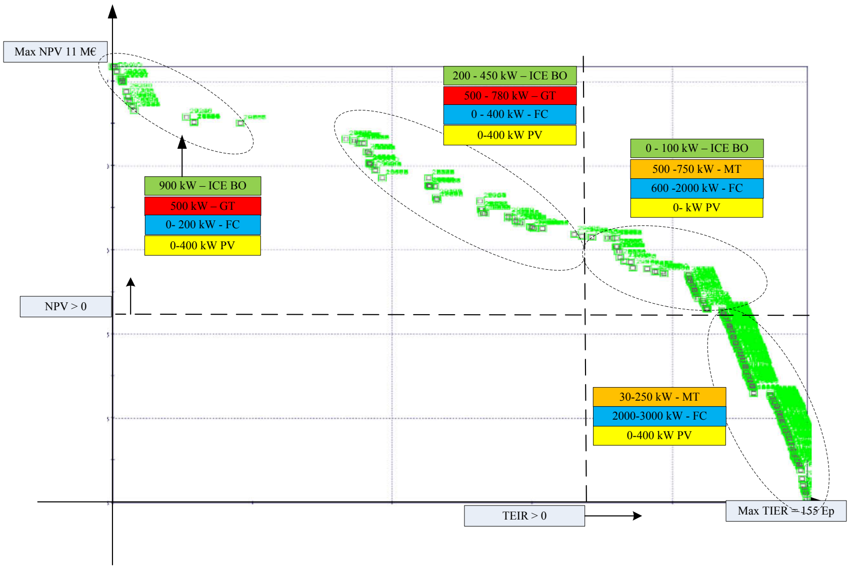


Figure 6.16: Pareto front for Company 3, Scenario 1

Despite the apparent similar situation of previous companies, featuring economic profitability linked to national incentives, the Pareto Front for Company 3 in Figure 6.16 shows that there's a range of economically-viable and environmental sustainable solutions with positive NPV and TIER, on the upper-right part of the graph.

However, there's still to evaluate the reliance of such solutions to national incentives, topic which will be treated in the next paragraph.

6.3.2 Scenario 2

The results of simulations for Company 1, considering the second scenario of absence of incentives are shown on Figure 6.17.

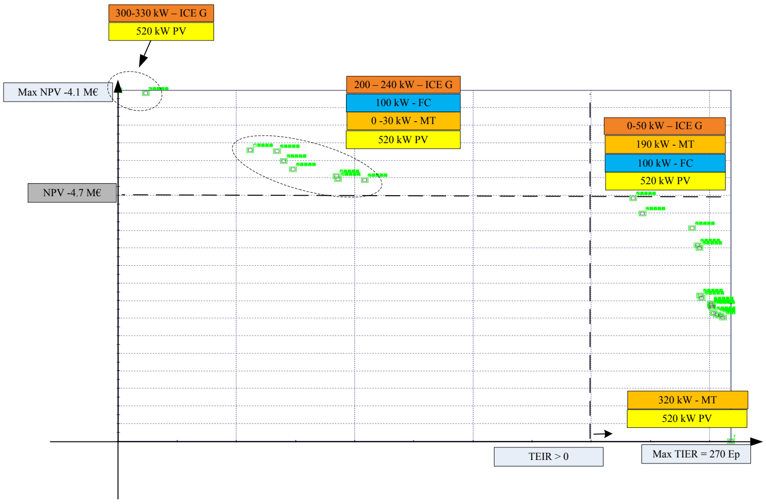


Figure 6.17: Pareto front for Company 1, Scenario 2

As expected from the assessment of Scenario 1, no solution could have been found being at least profitable. The top-left part of the Pareto Front – the latter presenting an apparently low accuracy even doubling simulation time and initial DOE – shows that the most “profitable” solution – a combination of Natural Gas Engine (300/330 kW) and a PV plant (520 kW) – presents a negative NPV (-4.1 M€). Logically, the installed power of the combination of plants, is similar to the one identified on Scenario 1 (about 800 kW) with difference associated to the variable performances (electric efficiency) by the various simulated solutions. PV plants accounted again large quota of installed power (520 kW) while combinations of FC and MT (100 kW and 320 kW maximum, respectively) constitute allows the best performances in terms of best environmental impact reduction. Results for Company 2 are shown on Figure 6.18

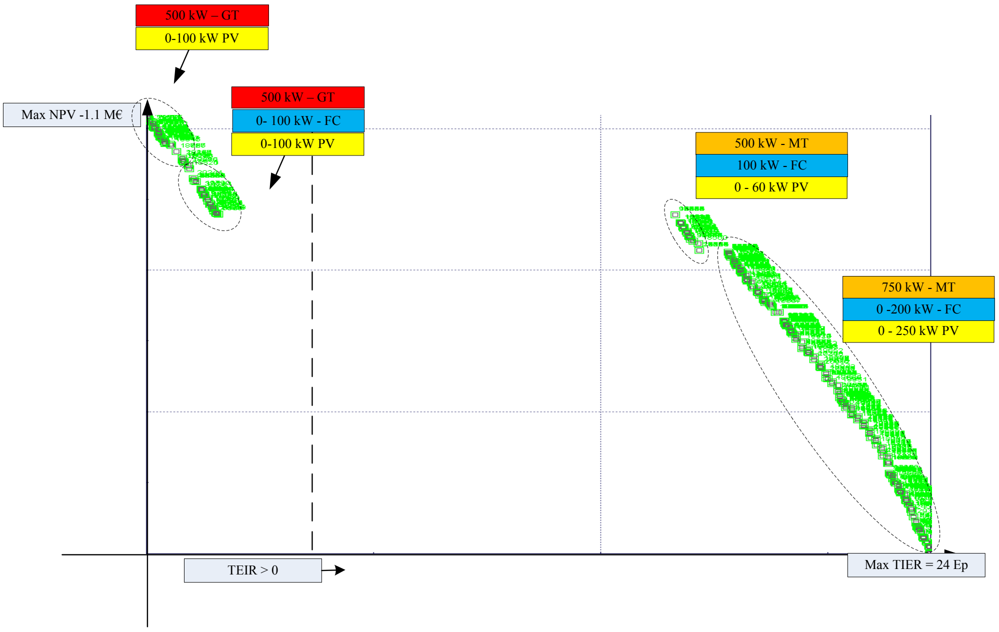


Figure 6.18: Pareto front for Company 2, Scenario 2

The whole range of feasible alternatives lies below the profitable solutions line (NPV > 0), with combinations of Gas Turbines, FC and PV plants for on the left of the of the graph, thus considering impacting solutions, while combinations of Micro Turbines, Fuel Cells, and PV in the right side of the graph, accounting for solutions whose emissions’ impact is lower than the saved impact from auto-producing energy.

Eventually, the assessment of Company 3 is represented on the Pareto Front of Figure 6.19.

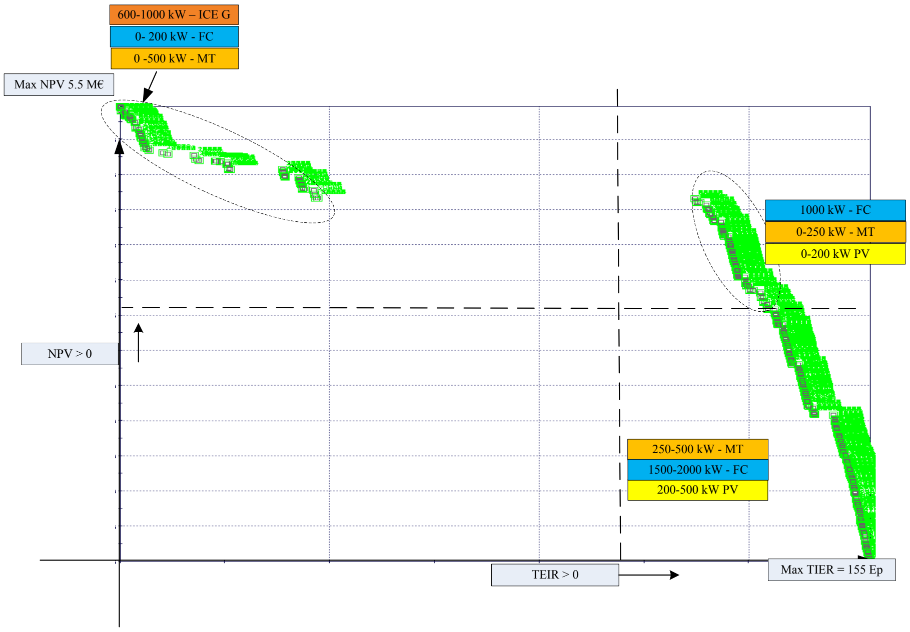


Figure 6.19: Pareto front for Company 3, Scenario 2

A broad range of economically viable solutions is available for the company, relying on combinations of gas-fuelled ICE, fuel cells and micro-turbines. However, it is interesting to assess that for this company, presenting both relevant heat and power loads, a range of profitable, environmental-friendly and incentive-free solutions exists, relying on FC, MT and PV plants, with larger-size combinations of those plants accounting for less impacting, but also with negative profitability, solutions.

7

DSS for Industrial Areas

The projects described in this last chapter refers to an application of the whole methodology presented in chapter 3 (reported on Figure 6.1) for the specific case study of an Industrial Area, namely the Kwinana Industrial Area (KIA), located in Perth, Western Australia. The project has been undertaken from January 2011 to June 2011, during the visiting period at the Centre of Excellence in Cleaner Production (later renamed to the "Centre for Sustainable Engineering") and has involved the assessment of some of the companies located in the KIA.

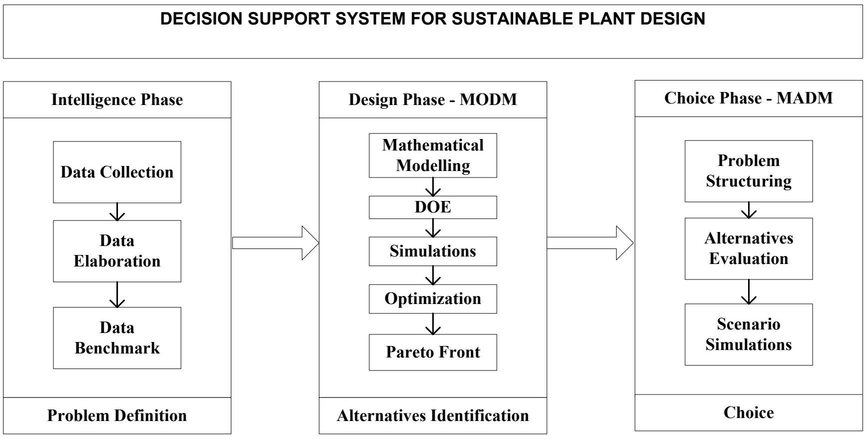


Figure 7.1: Methodological aspects treated in the section

The project considered all the stages of the methodology previously described:

- Intelligence phase: data collection by electronic survey and access to national database; internal benchmark of KIA environmental emissions and impact; external benchmark of companies' performance indicators;
- Design phase: application of the multi-objective modeling to the specific case of a surveyed company;
- Choice phase: application of the AHP methodology to the results of the previous stage, in order to choose an alternative among the previously identified ones.

These phases will be reviewed in the following paragraphs, anticipated by a brief contextualization of the Kwinana Industrial Area.

7.1 Australia: Strategy for Ecologically Sustainable Development

While the objectives and guiding principles of Australian policy for Sustainable Development (1992) are similar to those prescribed by the Agenda 21 (see Table 7.1), the research areas are initially referred to the environment protection field, related to sector-specific issues such as agriculture, fisheries, forests, manufacturing, mining, transports, tourism and energy. Cross-sectorial issues are then treated by the Australian Strategy, including broader sustainability aspects to the national policy, such as industry and trade relations, public health, occupational safety and employment, population issues and research/development.

Table 7.1: Australian National SD policy guidelines

Objectives	**Principles**
Economic development safeguarding future generations; Intergenerational equity; Bio-diversity protection.	Integrating economic, environment, social and equity consideration; Precautionary principle; Global dimension of environmental impacts; Strong and diversified economy; Environmental sustainable competitiveness; Cost-effective policy instruments; Participatory approach

7.2 The Kwinana Industrial Area

The Kwinana Industrial Area (KIA) is located close to Perth (Western Australia), and is characterized by a relevant presence of heavy industries such as refineries (crude oil, alumina, titanium dioxide, nickel) and chemical production, together with regional utility plants for power production and water treatment. Map and some of the most relevant figures of KIA are presented in Figure 7.2

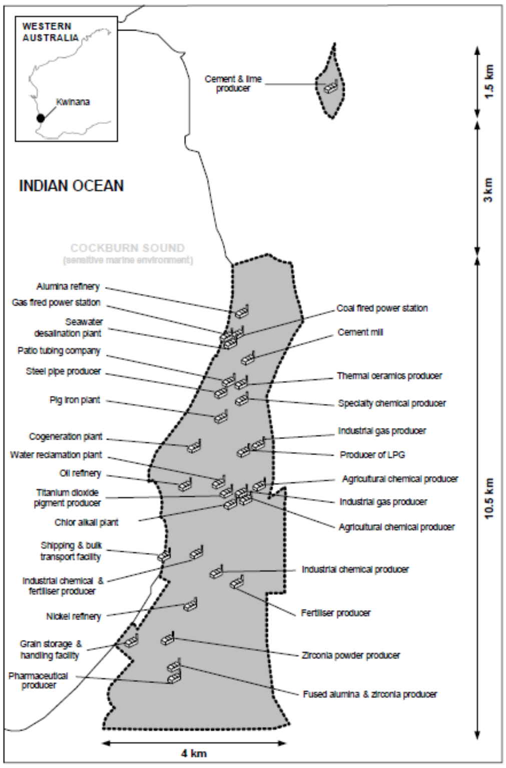


Figure 7.2: The Kwinana Industrial Area. Source: (Van Beers, 2007)

With the exemption of the local port authority ("Fremantle Port Authority") and some small/medium manufacturing enterprises, three major groups of companies are present in KIA,:

- *Heavy industry*: crude oil refinery 135.000 barrels per day, alumina refinery 2000 kt/year, Nickel Refinery 70 kt/year, titanium dioxide refinery 105kt/y, cast iron foundry 800kt/y and a cement works 700 kt/t; fused materials;
- *Chemical industry*: Ammonia Nitrate, Fertilizer and Ammonia Production, organic chemicals, flocculants agents, herbicides and agricultural chemicals, Chloro-alkali plant;
- *Utilities*: power production 900 MW coal/oil plant and a 240 MW gas turbine plant, two combined cycle plants, natural-gas fuelled turbines with steam recovery of 116 MW, and 40 MW, two air separation plants, two water reclamation and desalinization plant and a grain transport and storage company.

7.3 Intelligent Phase

Given the short period during which the project was undertaken (about 5 months), the data collection stage used simplified electronic model which has been filled up by the company personnel. Furthermore, a central database has been used for collecting data on environmental emissions. Data elaboration consisted in the calculation of performance indicators and on the impact assessment of company's emissions, allowing to benchmark companies within both the KIA and externally to other similar companies or industry reference.

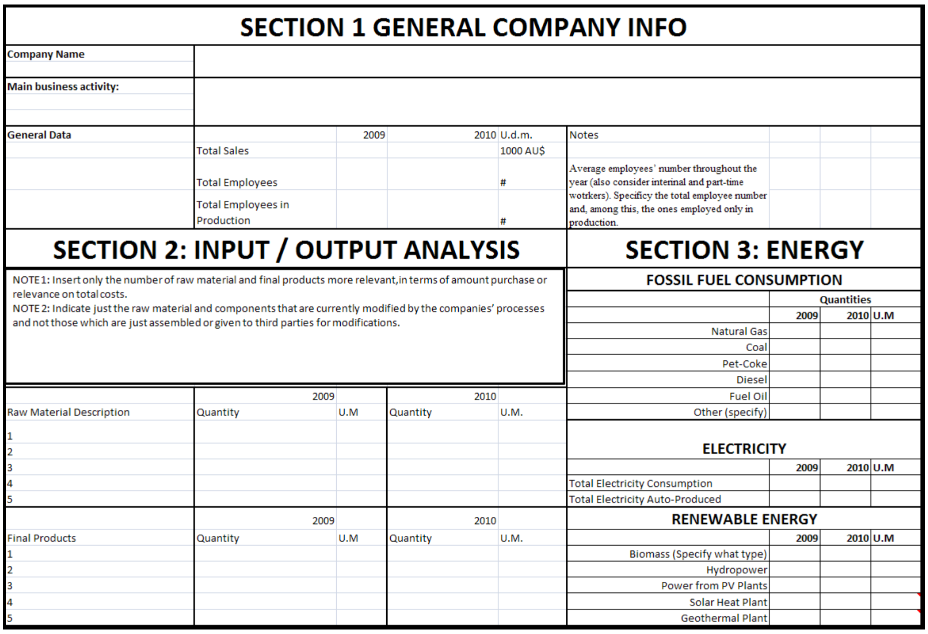
7.3.1 Data collection

Data collection for the companies in KIA has been carried out mainly by an electronic spreadsheet model, on-site visits to the company's premises, personal interviews to the company's personnel and access to a central database for environmental data.
The electronic model requested data on a yearly basis – 2009 and 2010 data were requested – regarding three main sections:

- General information and consumption data: company's name, main business activity, total sales, total employees, input/output analysis (raw material, components, final products), energy consumption (by type) and water consumption (by source);
- Air and water releases, divided by emitting/discharging point and toxicant;
- Waste production, divided by type and destination (re-used, land filled or treated onsite/offsite)

A snapshot of the utilized model is reported on Figure 7.3.

Given the difficulty in collecting the environmental Data, the study used as a reference the Australian National Pollutant Inventory (NPI, 2011), which is a database in which a list of 93 substances whose emissions have to be reported by the companies, when superior to a certain threshold of usage. Emission to air, water and land are recorded into this database. Direct calculation, estimation based on emission factors, mass balance or based on engineering calculation, represent the main ways proposed by NPI for calculating pollutants emission. Furthermore, the NPI database records the substances transferred to waste and designated to various destination such as destruction, landfill, storage and recycling, either onsite or offsite. The collected data, regarding to the first section, were too little for a comprehensive descriptive assessment. Collected data have been used for the elaboration step which will be analyzed later on.



SECTION 1 GENERAL COMPANY INFO

Company Name

Main business activity:

General Data		2009	2010	U.d.m.	Notes
	Total Sales			1000 AU$	
	Total Employees			#	Average employees' number throughout the year (also consider interinal and part-time wotrkers). Specificy the total employee number and, among this, the ones employed only in production.
	Total Employees in Production			#	

SECTION 2: INPUT / OUTPUT ANALYSIS

NOTE 1: Insert only the number of raw material and final products more relevant,in terms of amount purchase or relevance on total costs.
NOTE 2: Indicate just the raw material and components that are currently modified by the companies' processes and not those which are just assembled or given to third parties for modifications.

	2009		2010	
Raw Material Description	Quantity	U.M	Quantity	U.M.
1				
2				
3				
4				
5				

	2009		2010	
Final Products	Quantity	U.M	Quantity	U.M.
1				
2				
3				
4				
5				

SECTION 3: ENERGY

FOSSIL FUEL CONSUMPTION

	Quantities		
	2009	**2010**	**U.M**
Natural Gas			
Coal			
Pet-Coke			
Diesel			
Fuel Oil			
Other (specify)			

ELECTRICITY

	2009	**2010**	**U.M**
Total Electricity Consumption			
Total Electricity Auto-Produced			

RENEWABLE ENERGY

	2009	**2010**	**U.M**
Biomass (Specify what type)			
Hydropower			
Power from PV Plants			
Solar Heat Plant			
Geothermal Plant			

Figure 7.3: Snapshot of the online survey sent to the companies of KIA

7.3.1.1 Environmental Data Assessment

A Life Cycle Inventory (LCI) assessment was carried out using the NPI data collected for the KIA. Such stage, while representing a preliminary step to the latter stage of Life Cycle Impact Assessment, also allowed a preliminary benchmark of Industrial Park Performances. Before going on with the analysis, it should be noted that the NPI only accounts for substances emitted which exceed a specified usage threshold. Companies are required by law to report their emissions once they have exceeded this specified threshold. Some of the major thresholds contained within the NPI are reported in Table 7.2

Table 7.2: National Pollutant Inventory Thresholds

Category	Substances	Threshold
1	PAHs, Metals and others	10 tons per year
1a	Total VOCs	25 tons per year
1b	Mercury compounds	5 kg per year
2a	Fuels	400 tons per year
2b	Fuels, high usage	2000 tons per year OR 20,000 MWh per year
3	Total Nitrogen and Phosphorous	15 (Total N), 3 (Total P) tones.

The following analysis refers to the NPI 2009/2010 available data on the Kwinana Industrial state Area, including 34 Facilities subjected to reporting are localized in Figure 7.4

The bulk data on emitted substances reported by the NPI for the sampled companies are reported on Appendix D. The evaluation of the performances of the Kwinana Industrial Area has been done separately referring to the three main destinations of air releases (section 1), water discharges (section 2), while substance transferred to solid waste will be assessed in section 3.

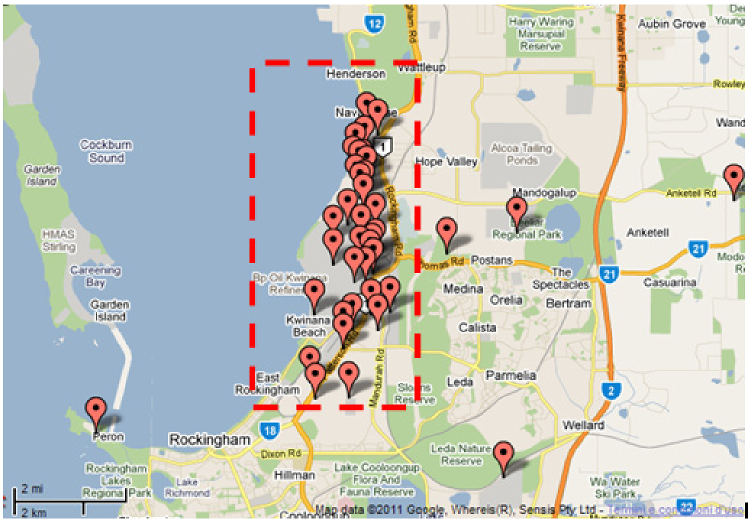


Figure 7.4: NPI-reporting companies included in the analysis

7.3.1.1.1Section 1: Air emission analysis

Air emissions represent by far the main pollutants emitted by the sampled KIA companies on quantity basis, amounting for the 98% of the total 31.4 kt pollutant registered. Assessing the impact of air emissions of KIA – thus evaluating the performances of the single companies – has to take into account a first distinction among the toxicant registered, that is:

- Macro-pollutants: substances - whose average air concentration is of the order of mg/Nm3 - and whose toxicity is evaluated by the amounts of toxicant released;
- Micro-pollutants: substances – whose average air concentration is of the order of µg/Nm3 or less – whose toxicity is evaluated by the quality of the specific toxicant released.

This first category encompass substance such as Carbon Monoxide, Oxides of Nitrogen, Particulate Matter, Oxides of Sulfur, while in the second category a broad range of toxicant are recorded, falling into sub-categories such as heavy metals, Polycyclic Aromatic Hydrocarbons (PAH), Volatile Organic Compounds (VOC) and other organic/inorganic compounds. Only macro-toxicant will be considered at this stage. In this category, the amounts of CO, NOx, SOx and PM will be assessed. The total macro-pollutants emitted in KIA amounts to 52kt, divided by NOx (32%), CO (25%), SO2 (38%), PM10 (4%) and PM2.5 (1%) The major contributors to such emission have been identified. A cut-off percentage of 1% has been applied for identifying only the major contributors.

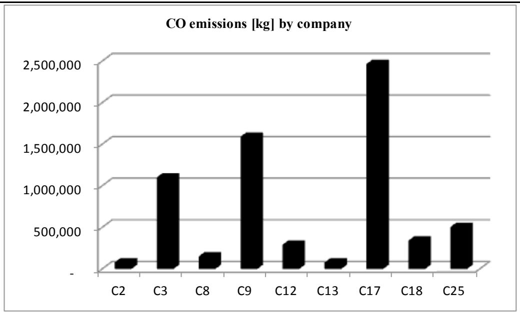
The applied cut-off for the macro-toxicants and the relative share of total contribution accounted is reported in Table 7.3

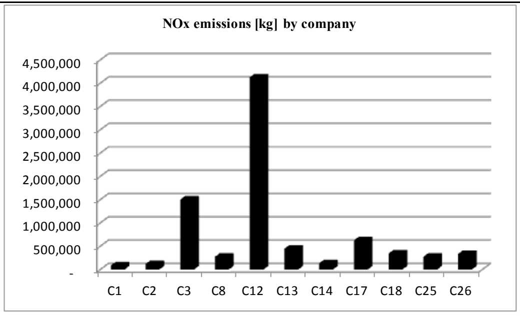
Table 7.3: Cut-off percentages for air emission analysis

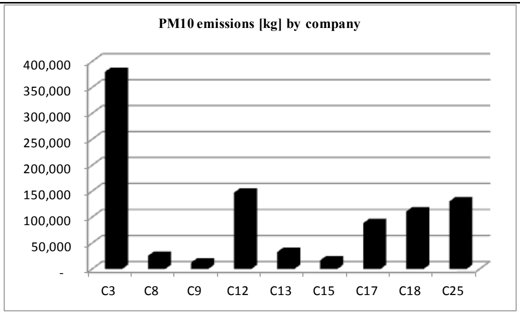
Macro-Toxicant	Share considered after 1% cut-off
Carbon Monoxide	97.9%
Oxides of Nitrogen	99.1%
Particulate Matter (10 µm)	97.2%
Particulate Matter (2.5 µm)	99.3%
Sulfur Dioxide	97.9%

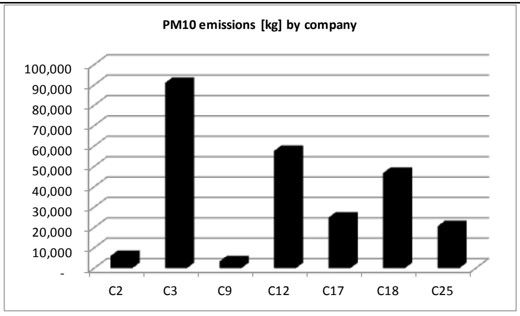
The results for the 5 major toxicant are reported on Table 7.4.

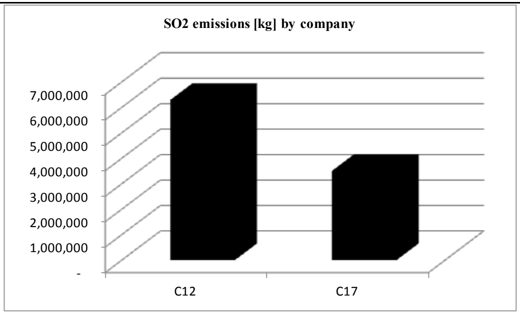
Table 7.4: Macro-toxicant emissions divided by company for 2010











7.3.1.1.2Section 2: Water releases

Water discharges account for a minor percentage (1.9%) of total KIA's emissions. The most relevant pollutants, on quantity base, are reported in Figure 7.5, where a cut-off the 0.1% was applied for identifying only major contributors. Boron, Fluoride and Manganese compounds, plus Ammonia and nutrients such as Nitrogen and Phosphorus account for 99.9% of total KIA's emission on quantity basis.

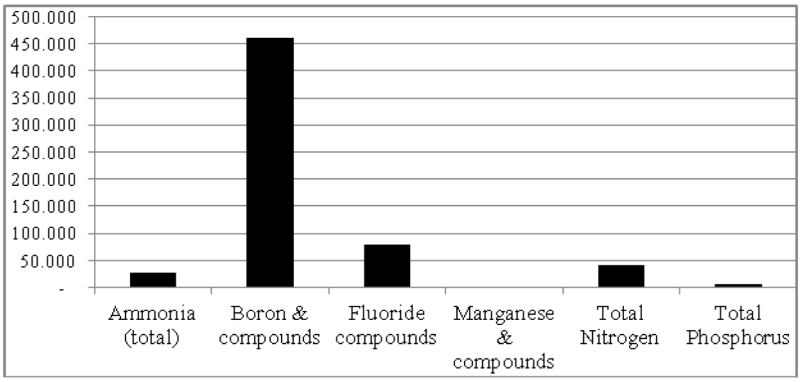


Figure 7.5: Water discharges of KIA's companies [kg/year]

7.3.1.1.3Section 3: Waste production

Substances transferred as solid waste are also reported in the NPI, following the same recording principles as air and water emissions discussed above, with the waste production only being recorded once they have exceeded the nominated threshold value. The amount of waste produced is recorded in terms of treatment location (onsite or offsite) and final destination (reuse, landfill, short-term and long term storage). Results for the Kwinana Industrial Area are shown in Table 7.5.

Table 7.5: Waste produced - occurrence and transfers - KIA

Location	Destination	Amount [kg]
Off-Site	A) Off-site destruction	249.1
	B) Off-site landfill	211,958.8
	C) Off-site long term waste storage	16,808.4
	D) Off-site recycling	104.6
	E) Off-site treatment (leading to mandatory destination)	168,000
On-Site	F) On-site landfill	1,644
	G) On-site long term waste storage	68,212
	H) On-site partial purification	6.5
	I) On-site recycling	62,000
	L) On-site remediation	200
	M) On-site tailings storage	4,017,992

The results shown in Table 3 highlight that the most significant amount of waste produced within the KIA is actually stored on-site/off-site (C+G+M = 90.2%) or landfilled (B+F = 4.7%). This is due in particular to the activities of one company and their large volume production of bauxite residue wastes (tailings storage) which are stored in stockpiled on the company premises. Aside from this bauxite residue waste storage, the remaining waste incurred within the KIA refers mostly and thermal destruction (A + E = 3.7%). Minor volumes of ‘reuse and recycle’ waste are also reported (D + I + L = 1.4%).

7.3.2 Data elaboration and benchmark

Data collected from the previous stage has been elaborated in order to provide indicators to be used for external and internal benchmark. Specifically, the following elaborations have been done:

- Performance indicator calculation
- Life Cycle Impact Assessment

which are assessed in the following paragraphs.

7.3.2.1 Indicators approach

Performance indicators have been calculated, especially referring to raw material treatment/refinery companies, for which a broad range of literature has been developed. BREF documents of the EU have been particularly used during this step, due to their ability to synthesize and group many previous assessments related to the specific activity. No direct reference could be done to company’s data due to confidentiality agreement.

7.3.2.1.1Energy and environmental performances of Titanium Dioxide production

The production of titanium dioxide (TiO_2) has been evaluated and benchmarked for a company in the sample. Titanium Dioxide powder is used in a range of applications. The process is particularly energy intensive: from synthetic rutile – which is produced off-site by leaching ilmenite in order to reduce impurities – the process involves a preliminary formation of $TiCl_4$ in Coke-fuelled furnaces, later on oxidized by reacting with synthetic oxygen and Toluene. The TiO_2 thus produced is milled and grinded, and presents a particularly white color, and sent to packaging. BREF documents (IPCC, 2011) specifically addresses TiO_2 production, assessing a total of 19 plants which differs from the main process used (chlorine- or sulfide- based). Data related to the chlorine-based process have been benchmarked with company’s values, reported on Table 7.6.

7.3.2.1.2Energy and environmental performances of a crude oil refinery

Crude oil refinery in Kwinana industrial Area consists in a two distillation units followed by a cracking unit for further recovery of heavy fractions. Further processing may be grouped in two main areas, that it:

- Product sweetening units, i.e. reducing mercaptans/sulphur content;
- Polymerization units, for modifying organic structure of the products by means of catalytic reactions.

Assessing the performance of crude oil refinery depends heavily on the diversified production of each location, which affects facility’s complexity in terms of installed plants. In Crude Oil refinery, a complexity index has been defined, accounting for such differences and synthesizing them in order to provide benchmark of worldwide complexes. Nelson index of the specific refinery is 7.6. BREF document of the IPCC on crude oil refinery presents performance data of 56 refineries in Europe, varying for size and complexity. By using the following table, the performances of the company have been compared to EU refineries with similar Nelson Index (from 6 to 9).

Table 7.6: Benchmark values for sustainability indicators

	U:M	AVG - IPCC	Max - IPCC	Min - IPCC
Raw Material	kg/t_{tiO2}	1075	1145	975
Chlorine	kg/t_{tiO2}	201	300	114
Coke	kg/t_{tiO2}	366	429	285
Oxygen	kg/t_{tiO2}	467	573	395
NaOH	kg/t_{tiO2}	104	178	7
Energy Usage	GJ/t_{tiO2}	24.8	28.7	17.4
Water	m3/t_{tiO2}	34.5	48	22.6
CO	kg/t_{tiO2}		181	83
Particles	kg/t_{tiO2}		0.4	0.1
SO2	kg/t_{tiO2}		0.3	0.1
HCl	kg/t_{tiO2}		0.2	0
Cl	kg/t_{tiO2}		0.00054	0.00012

Table 7.7: Benchmarking some of crude oil refinery's sustainability indicators

	IPCC - MIN	IPCC - MAX	IPCC - AVG
Energy use	1.6	4.6	2.75
Water consumption	0.13	11.91	5.78
Carbon Monoxide	10	415	53
Nitrogen Oxides	59	460	249
Particulate Matter (PM10)	0.1	45	15
Particulate Matter (PM25)	0.01	12	4
Sulfur Dioxide	52	1565	741
TVOC	65	4628	1426

7.3.2.1.3Energy and environmental performances of Alumina Refinery

Alumina refinery located in Kwinana relies on a two-step process of bauxite digestion (a cycling leaching process in an extremely caustic environment), leading to a calcination process, followed by grinding and milling processes. Eventually, chemical upgrading is used for producing graded Alumina.

The impacts of this complex process are numerous, however the most relevants are related to:

- Energy consumption: calcination and digestion processes accounts for the majority of the energy consumed;
- Water consumption, used during the digestion batch process;
- By-product waste production: red mud and silicates sand are the main by-products of the leaching process. The first one has to be stabilized (its highly alkaline PH has to be neutralized) before being treated for water purification, while several applications of the second have been studied, as reviewed by (Power, 2011).

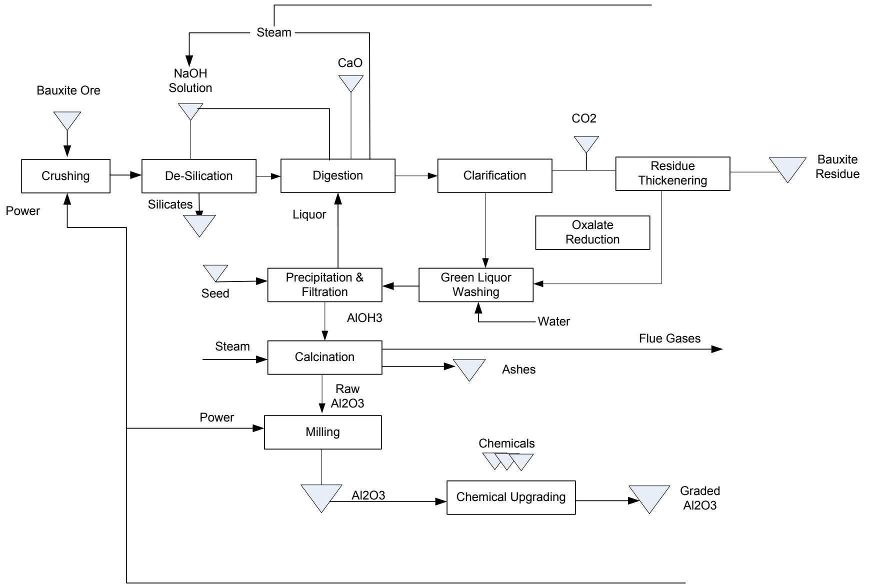


Figure 7.6: Alumina refinery process flow. Elaborated from (IPCC, Joint Research Center, 2011)

Benchmark values have been provided to the company.

Table 7.8: Benchmarking some of Alumina Refinery's sustainability indicators

	UDM	$IPCC_{min}$	$IPCC_{MAX}$
Bauxite Use	t/t_{Al203}	2.1	2.3
Energy use	GJ/t_{al203}	7.6	11.7
Water consumption	t/t_{al2o3}	1	5
NaOH (50%)	kg/t_{al203}	30	70
Bauxite Residue Production	t/t_{al203}	0.6	1.5

7.3.2.1.4Energy and environmental performances of powder sintering

A company in KIA producing grains of alumina, silica and zirconia by sintering (heating below the melting point) such raw materials in electric arc furnaces, has been assessed. Company's specific electricity consumption in terms of kWh consumed per ton of final product has been compared to literature references. Data received from the company regards energy consumption and input/output analysis have been used to calculate the specific amount of electricity consumed per ton of final products, specifically referring to fused Alumina (Al2O3 grains) and fused zirconia and silica fume. (Zeng, Gao, Gui, & Guo, 1999) Identified the following activation energy requirements for Al_2O_3 powder (see Table 7.9).

(P.Cichy, 1972) relates a specific energy consumption variable between 1370 and 1870 kWh/ton, while references from (Washington Mills, 2011) relates an approximate electricity consumption of 2000 kWh/ton. Considering the molecular weight of alumina (101.94 g/mol) and converting to a unique unit of measurement, company's energy consumption indicator – considering the total amount of Al_2O_3 produced in 2010 - has been benchmarked to such values.

Table 7.9: Specific energy consumption for white alumina power

Diameter (µm)	**State of agglomerate**	**Activation Energy [KJ/mol]**	**Activation Energy [kWh/ton]**
0.2 – 0.5	Agglomerated	627	1708
1 – 2	Dispersed	481 ± 41.8	1310
3 – 5	Dispersed	893	2433
0.01	Soft agglomerated	357	973
0.01	Hard agglomerated	481	1310

A similar research has been conducted for fused zirconia. Silica fumes, as by-product of fused zirconia production, have not been considered in this assessment. (Chaim, 2008) reported an activation energy for Yttria-stabilized Yetragonal Zirconia Polycrystals ranging from 280 and 546 KJ/mol at reaction temperatures of 1400°C, equivalent to 1254 and 2446 kWh/t, considering the approximate Y_2O_3 doping of 3%.

7.3.2.2 Life Cycle Impact Assessment

Emissions reported in the NPI database have been used for evaluating the *impacts* (rather than the outputs) of the Kwinana Industrial Area. A relevant preamble has to be made. the following analysis does not want to represent the actual impact caused by companies' emission – which should require far more specific analyses – but it represents a tool for identifying, quantifying and improving potential impacts of company's emitted pollutants, thus helping decision makers to identify top-priorities of current sustainability management for preventing future impacts.

The Life Cycle Impact Assessment methodology chosen for the study was 'Eco-Indicator 99', as explained on chapter 3 two main impacts have been considered in this study, namely:

- Human Health;
- Ecosystem Damage;

In Eco-Indicator 99, 'human health impacts' are measured in 'Disability Adjusted Life Years'(DALY) which measures the number of 'life' years lost due to the inhalation/ingestion of particular substances via different sources (e.g. air, food, water). In Eco-Indicator 99, 'ecosystem impacts' are measured via the 'Potentially Disappeared Fraction'(PDF) of animal and natural species measured(per square meter per day). Considering the wide range of impacts of the Eco-Indicator methodology, only the latter two have been considered due to the lack of Australian-specific impact factors regarding the others. The human health and ecosystem specific impacts (per unit of pollutant emitted/discharged) – have been computed by (Lundie, Huijbregts, & Rowley, 2007) and have been used in this study.

7.3.2.2.1Human Health impact of KIA

Human Health impact is calculated considering both carcinogens and non carcinogen effects (e.g. respiratory). Focusing on air emissions, Most relevant toxicant, recorded by the NPI for the KIA, have been calculated using a cut-off percentage of 0.1% (on the total human toxicity impact) and are reported in Figure 7.7a. The cut-off allowed to reduce the total number of toxicant considered (from 56 to 8) while considering the most impacting pollutants, which account for 99.6% of total impact. Among such restricted group of toxicant, Arsenic, Cadmium, Mercury and Selenium compounds account for the majority (97.5%) of total KIA's impact. Similarly, Kia Ecosystem

Impact has been calculated using a cut-off percentage of 0.1%. The first assessment showed that Fluoride Compounds Impacts accounted for 99.91% of total KIA's Ecosystem Impact. The toxicity of fluoride compounds has been studied extensively in literature and reviewed by (Camargo, 2003), but despite its toxic effects, the damage factors used by the reference model appeared to be excessive, also considering that seawater impact is considerably higher than freshwater one (Lundie, Huijbregts, & Rowley, 2007), while the literature referenced affirms the opposite. Therefore it has been considered appropriate calculate the major companies contributing to Eco-System Toxicity excluding the effects Fluoride Emissions, waiting for a more accurate evaluation of its effects. Adjusted results are reported on Figure 7.7b: seven main toxicants have been identified, with Nickel, Mercury, and Selenium accounting for the 83% of company's eco-toxicity impact.

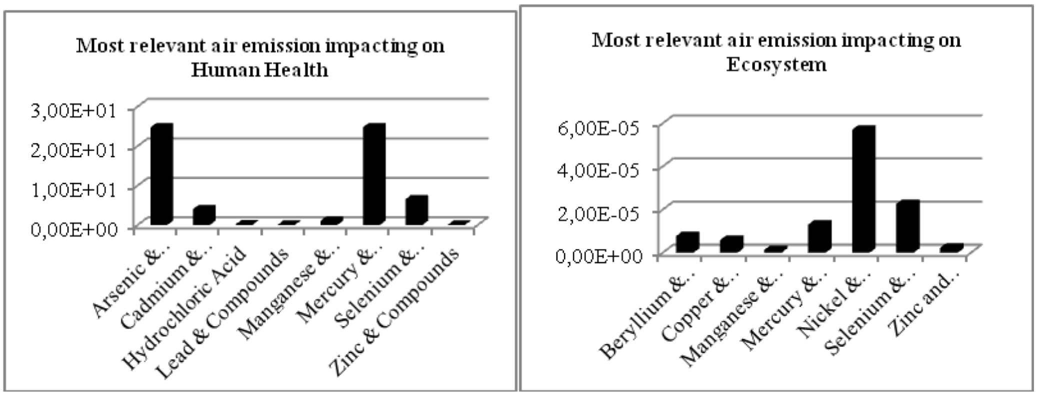


Figure 7.7: KIA's air emission impact assessment on Human Health (a) and Ecosystem (b)

Arsenic and mercury's emissions are the most relevant pollutants to be assessed for human-health impact assessment, while nickel and selenium compounds are to be monitored regarding their potential ecosystem impact.

Similarly to what considered for air emissions, micro-pollutants impacts have been considered for the water-discharged substances in KIA recorded by the NPI. The cut-off percentage of 0.1% allowed to reduce the number of toxicant from 56 to 8 (Ecosystem) and 6 (Human Toxicity), while accounting for the majority of the impact on the ecosystem (99.86%) and human health (99.8%). The most relevant toxicant discharged are reported in Figure 7.8a and Figure 7.8b, related to Human and Ecotoxicity.

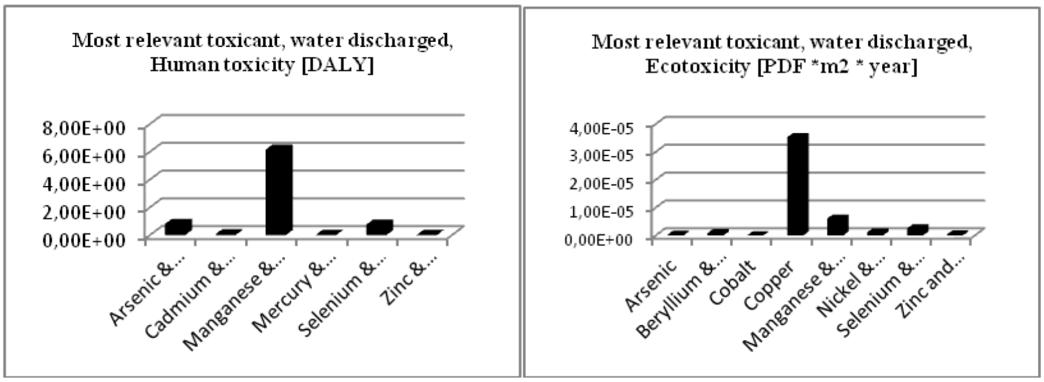


Figure 7.8: KIA's water discharges impact assessment on Human Health (a) and Ecosystem (b)

Manganese represents by far the most relevant toxicant to be monitored for avoiding human health impact by water discharges, while Ecotoxicity copper compounds needs to be considered by local authorities. Having identified the most relevant toxicants to be monitored by companies and local authorities, the last step have been that of identifying the most relevant companies related to such impacts. Results are shown on Figure 7.9 and Figure 7.10.

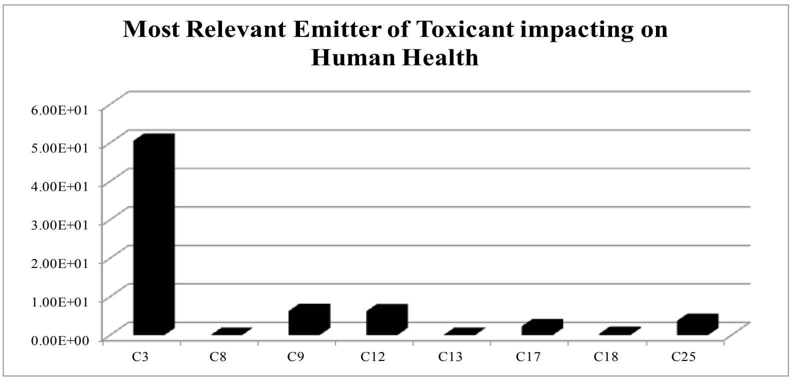


Figure 7.9: KIA's most relevant companies impacting on Human Health

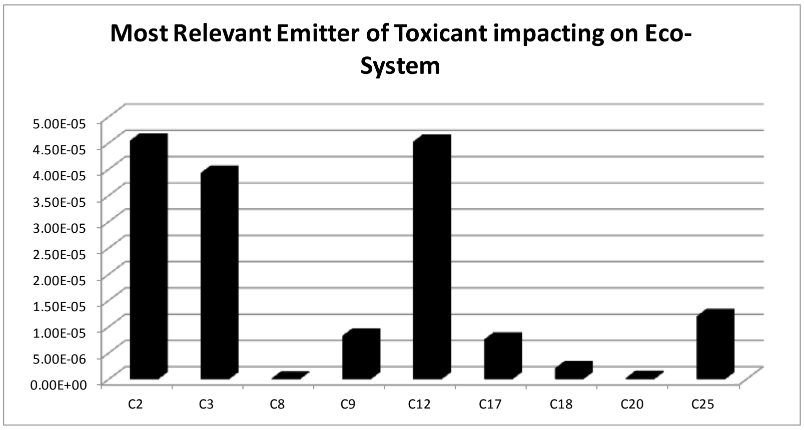


Figure 7.10: KIA's most relevant companies impacting on the Eco-System

7.4 Design Phase

In this step the methodology presented on section 3 will be utilized for a specific case study of a company located in the KIA. The company produces chemical agents (flocculants) for water treatment mainly for the nearby companies in the KIA. Company's main data have been collected by direct interview of company's personnel, gathering information regarding productive cycle, power consumption and costs, natural gas consumption and costs to be used in the modellization reported in chapter 3.

After having considered Australian-specific power and natural gas prices, the following modifications had also to be considered in order to assess Australian-specific conditions:

- Electricity and natural gas price increases have been particularly relevant in the country over the last years. A value of 11% and 10% have been considered by the government sources (Government of Western Australia, Office of Energy, 2011);
- At the moment of the simulation (October 2011) no incentives for renewable power production exist for businesses, while net-feed-in tariffs are used for household applications. Given such considerations, the simplified modellization stage did not consider bio-oil plants – whose supply chain is basically nonexistent at the studied context. Only Gas-fuelled ICEs, MT and GT, FC and PV plants were thus assessed;
- A further constraint has been added to the model in order to avoid multiple-plants selection of CHP plants from the simulator. By adding this constraint, only combinations of *one* CHP plant and PV systems could be selected by the optimizer.

The following scenario has been considered:

- Scenario 1: Base-Scenario with market based prices and trends in fossil fuel and power prices;
- Scenario 2: Base Scenario with an increased fossil fuel load (+25%) due to an expected increase in product capacity particularly requiring hot water heating (60°C);
- Scenario 3: Base-Scenario with diminished trends in fossil fuel and power prices, arbitrary chosen at 7% and 8%.

7.4.1 Scenario 1

Base-load scenario led to the peculiar situation of Figure 7.11

The Pareto Front is made by four single-point solution, which are:

- Combination of gas-fuelled ICE (370 kW) and PV plant (110-120 kW), located in the top left of the figure above.
- a 300 kW Fuel Cell coupled with a 180-190 kW PV plant. (top-right and bottom right respectively);

The fact that only few feasible solutions exists might be better assessed by looking at the Figure 7.12, showing the whole ranges of feasible alternatives which have been assessed by the simulator. As shown, the simulator gradually assess the feasible points, which, for the specific case study are related to combinations of gas-fuelled-ICEs or Fuel Cells, and PV plants. Other solutions (gas and micro turbines) didn't respect the current limit on excessive waste heat output while simultaneously satisfying at least 70% of company's needs. On the top left side, the most profitable solution of the selected group presents a NPV barely positive (85 k€), while its environmental impact reduction is negative (more pollutants are emitted than the effective emission savings). On the top-right most impact-reducing solution presented a TIER of 19.7 Ep and an economic profitability of 82 k€, similar to the previous one, while on bottom right the Pareto Front solutions presents comparable value of TIER, but reduced profitability.

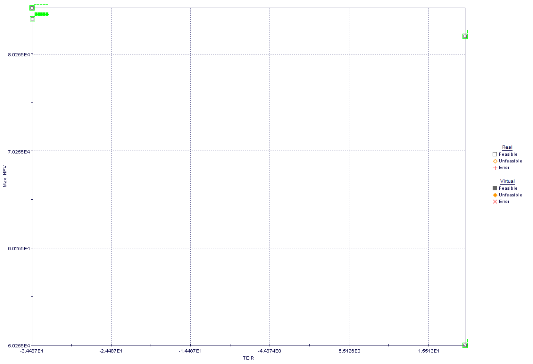
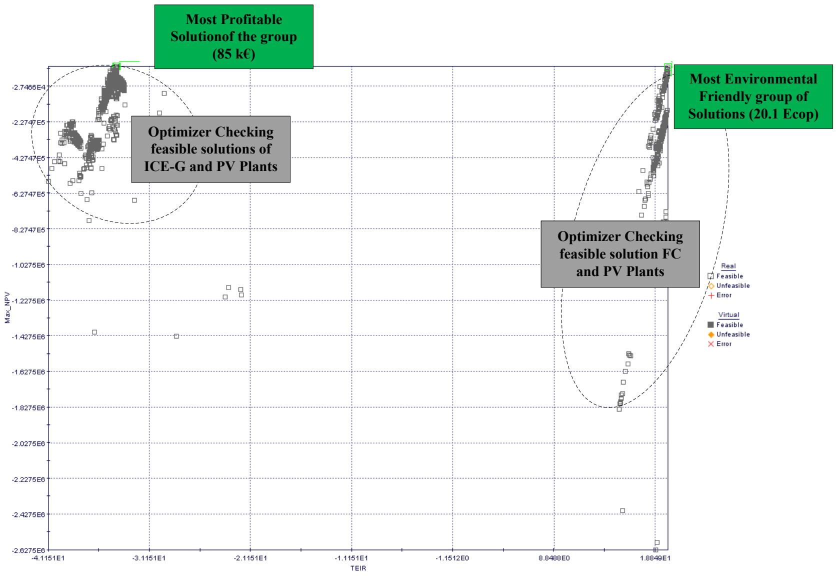


Figure 7.11:Pareto Front for Company, Scenario 1


Most Profitable Solutionof the group (85 k€)

Optimizer Checking feasible solutions of ICE-G and PV Plants

Most Environmental Friendly group of Solutions (20.1 Ecop)

Optimizer Checking feasible solution FC and PV Plants

Figure 7.12:Pareto Front for Company, Scenario 1, details

7.4.2 Scenario 2

Increasing the fossil fuel consumption by 25% led to the Pareto Front of Figure 7.13

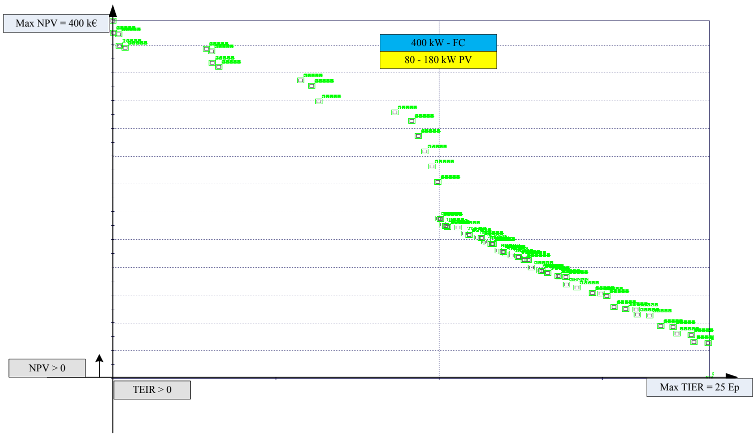


Figure 7.13:Pareto Front for Company, Scenario 2

The Pareto Front is made only by profitable and environmental friendly solutions, evolving the top-right quadrant of Scenario 1, thus considering combinations of PV plants and FC has alternatives solutions, with PV plant as a discriminating factor between environmental performances increases and reduced profitability. The combination of ICE and PV plant has not been considered into the Pareto Front, thus assessing the whole space of feasible solutions, as shown on Figure 7.14, it's shown that the optimizer had taken into consideration such combination, which presents similar – but lower - features of profitability of the Pareto Front, and has thus been excluded by it.

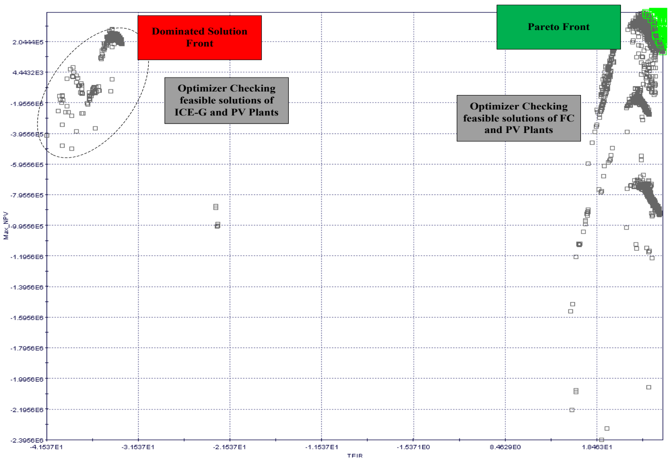


Figure 7.14: Pareto Front for Company, Scenario 2, optimizer details

7.4.3 Scenario 3

Eventually, a decrease in fuel and power price trends from the current 10/11% to inferior values (7% power and 6% natural gas) has been studied (not reported), showing that the Pareto Front is completely in the negative side of the profitability axis. The reduction of yearly price increase resulted in a negative profitability, quite expected given the already-low values of profitability registered for the NPV over 20-years of the previous scenarios.

7.4.4 Alternatives selected for the choice phase

Having assessed the robustness of the simulations, the following alternatives have been considered for further study of stage 3 (“Choice Phase”), that is.

- Gas- Fuelled Internal Combustion Engine combined with PV plant
- Gas Fuelled Fuel Cell combined with PV plant

Technical details about the solutions are provided on Table 7.10

Table 7.10: Alternatives benchmark, quantitative criteria

		UM	Solution 1	
Technical Criteria	CHP Plant Type		ICE	FC
	Plant Model and Brand	-	MDE (Tognum) MB 3042	Hydrogenics HyPM™ HD 100
	Power Efficiency	%	39%	54%
	Thermal Efficiency	%	45%	41%
	PV Plant Type		Suntech STP070-12/Sb	Sunpower e20/333
	Efficiency	%	14%	20%
	Occupied Area	m2	1,050	1,050
	Power Produced by PV	kWh	161,663	234,965
	Total Power Produced	kWh	1,255,568	1,138,810
	Percentage	%	100%	91%
	Total Heat Produced	kWh	1,259,469	685,431
	Percentage	%	230%	125%
Economic Criteria	Capital Costs	€	827,228	1,606,384
	Operating Costs at y=0	€	201,911	163,517
	Operating Revenues at y =0	€	212,469	198,905
	Payback	years	19	19
	NPV	€	120,164	170,775
	IRR	%	15%	11%
Environmental Criteria	CO2 emissions	t	193.82	365.8
	CO emissions	t	-15.51	0.64
	SOx emissions	t	3.06	2.78
	PM emissions	t	0.05	0.08
	NMVOC emissions	t	-0.11	0.00
	NOx emissions	t	-7.95	1.52

Eventually, Business as Usual (BAU) scenario has been considered, in order to benchmark the proposed alternatives with current scenario. Data of such alternative is reported on Table 7.11.

7.5 Choice Phase

Having identified the feasible solutions from the both techno-economic and environmental criteria, the last step of the methodology involves the structuring of a decision making model for final choice among the identified solution set.

In order to do so, the AHP methodology has been used, as presented in chapter 3. The following steps have been considered.

- Problem Structuring;
- Pairwise comparison;
- Aggregation and results.

Table 7.11: Quantitative criteria for Business-as-Usual Scenario

	Criteria	UM	BAU scenario
Economic Criteria	Capital Costs	€	0.00
	Operating Costs at y=0	€	188050.00
	Operating Revenues at y =0	€	0.00
	Payback	years	100.00
	NPV	€	-5.923.271,00
	IRR	%	0%
Environmental Criteria	CO2 emissions	t	-763.7
	CO emissions	t	-0.84
	SOx emissions	t	-3.06
	PM emissions	t	-0.1
	NMVOC emissions	t	-0.02
	NOx emissions	t	-1.81

7.5.1 Problem structuring

In this stage the criteria used during the assessment have been identified. The previous stage involved only a two-objective function in order to identify trade-off ranges, but, given the various issues to be involved in the decision making process, a more detailed problem structuring has been considered. Specifically, 4 categories of criteria have been used:

- Technical Criteria
- Economic Criteria
- Environmental Criteria
- Social Criteria

which are detailed in the following paragraphs

7.5.1.1 Technical criteria

In this category the technical criteria for benchmarking the alternatives have been considered. Specifically, the following criteria are to be used:

- T1: Alternatives efficiencies, further divided in CHP electric efficiency (in terms of power to fuelled-energy ratio, referred to the CHP technologies, T1A), PV electric conversion efficiency (T1B) and thermal efficiency of the CHP plants (T1C);
- Percentages of company's satisfied needs (thermal, T2A, and electrical, T2B);
- Technological reliability, in terms of commercial development and subsequentialy easiness – economic and logistic - of plant acquisition (T3).
- Percentage of covered area from the PV plant (T4)

7.5.1.2 Economic criteria

This category, particularly relevant in the decision making process, encompasses:

- NPV of the considered solution, as previously introduced (E1);
- Payback, i.e. the number of years for returning from the initial capital expenditure (E2);
- Initial Capital Investment (E3);
- IRR (Internal Rate of Return), considered as the ratio between the NPV and the capital investment.

7.5.1.3 Environmental Impact

Emissions, whose human health impact has been considered at the design stage, have also been taken into account into this category, also relating them to the other impact categories of eco-system impact and resource depletion. Net CO_2 emission have also been considered, given the particularly relevance in the Australian context, where carbon pricing might be soon introduced in national legislation. Therefore, the following criteria have been considered, coherently with the impact assessment mode previously considered. :

- Human Health Impact divided per NOx (E2A), CO (E2B), SOx (E2C), VOCs (E2D), PMs (E2E);
- Ecosystem Damage, divided per NOx (E2A), CO (E2B), SOx (E2C), VOCs (E2D), PMs (E2E);
- Resource consumption (Fossil Fuel consumption, E3).
- CO_2 emissions

7.5.1.4 Social Impact

Eventually, in this last category, the non-tangibles values referring to the installation of the new plant are considered. Specifically, the model considered:

- Corporate 's attitude (S1)
- Company's director attitude (S2);
- Facility's manager attitude (S3).

The final hierarchic model is represented on Figure 7.15

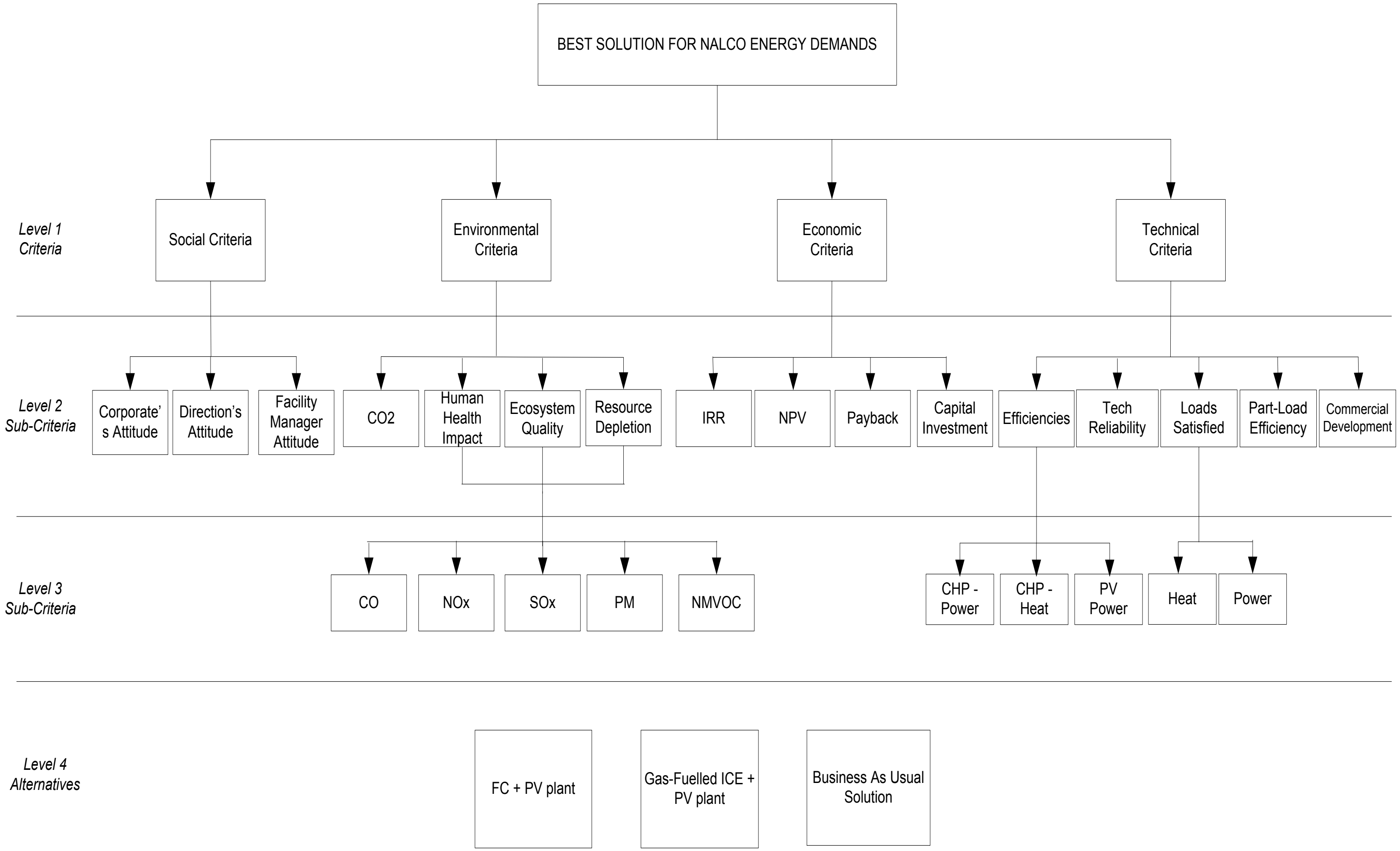


Figure 7.15: AHP model for alternatives benchmark

7.5.2 Pairwise comparison

The three identified alternatives have been compared considering the hierarchy previously described. Observing the latter, three main types of comparison have been identified:

- Alternatives vs. Level 4 criteria (e.g. CO emissions).
- Alternatives/Level 3 vs. Level 2 criteria (e.g. NPV, Human Health impact of CO emissions);
- Level 2 criteria vs. Level 1 (e.g. Environmental Impact of Human Health)
- Level 1 criteria vs. Main Goal (e.g. Environmental impact vs. Best Solution).

7.5.2.1 Alternatives vs. Level 4 criteria

In this category two main groups of comparison have been executed:

- Alternatives evaluation considering pollutants emissions;
- Alternatives evaluation considering technical features such as efficiencies and loads satisfied:

Comparison of alternatives' emissions is quite straightforward due to the use of quantitative values, reported on Table 7.10 and Table 7.11. The AHP software "Superdecisions" does not allow negative values direct entry, therefore emission values had to be normalized in order to assess both positive (emission-reducing alternative) and negative (emission-adding alternative) values. Normalization has been done by considering the method presented on chapter 4, considering:

- Calculation of the difference between the maximum value and the alternative's value;
- Absolute value of the difference of normalized values for pair wise comparison;
- Transformation (by proportion) of the difference in the 1-9 Saaty scale

Another slight modification to quantitative has been done considering a surplus of heat production as a negative factor, due to the need of heat disposal. Such modification has been done by considering the following equations:

$$if\ \left(\frac{HP}{SL}\right) \leq 1;\ SL = \frac{HP}{HL};$$
$$if\ \left(\frac{HP}{SL}\right) > 1;\ SL = 1 - \frac{HP}{HL}$$

When the Heat Produced (HP) is greater than the Heat Loads (HL), the Satisfied Loads (SL) is calculated as a difference between the 100% value and the measured ratio. When HP is smaller than the HL, the ratio is taken as simply calculated. Thus, the case of an excessive heat produced (HP = 1500 MJ and SL = 1000 MJ) is considered equal to a partially-satisfied loads (HP = 500, SL = 1000) due to the fact that a higher load has to be disposed of and it thus represents a system inefficiency, as well as a lack of produced energy. Different weight associated to such factors might also be used.

7.5.2.2 Alternatives/Level 3 criteria vs. Level 2

In this category, a broad range of comparison has been executed, divided into the following groups:

- Level 3 criteria vs. Level 2 assessments, namely:
  - Relative impacts of pollutants on Impact categories (Human Health and Ecosystem);
  - Plants efficiencies vs. Efficiency criteria;
  - Heat and Power needs vs. Satisfied Needs criteria.
- Quantitative evaluations of alternatives respect of level 2 criteria, namely:
  - Environmental Criteria: CO2 emissions, Resource Depletion;
  - Economic Criteria: NPV, Payback, IRR and Capital Investment;
- Qualitative evaluations of alternatives respect of level 2 criteria, such as:
  - Technical Criteria such as Commercial development, part-load efficiency and technology reliability;
  - Corporate/company's and facility manager's attitude towards alternatives;

Level 3 criteria vs. Level 2 assessments

Pollutants impact on Human Health and Ecosystem damage has been done by considering the Impact Factor introduced in the work in relation to the Human Health impact of the optimization model. Similarly, Ecosystem Damage Factors, expressed in potentially disappeared fraction (see Chapter 3) per m^2 per year, have been used in this section, with impact factors reported in (Goedkoop & Spriensma, 2011). Ecosystem and Human Health Impact factors are reported on Table 7.12.

Table 7.12: Impact Factors of Macro-Toxicant emissions

	Human Health Impact [DALY/kg]	Ecosystem Damage [PDF/m2 year]
NOx	5.76 E-3	5.713
SOx	3.55 E-3	1.041
CO	7.31 E-7	-
PM 10 PM 2.5	2.44 E-2 4.55 E-2	-
NMVOC	8.26 E-5	-

Plant efficiencies (heat and power) comparison have been considered equally important when assessing the total relevance of the criteria, and the same has been considered to heat and power loads satisfied.

Quantitative evaluations of alternatives respect of level 2 criteria

Such quantitative comparison did not provided any difficulty when comparing alternatives. Referring to Payback value, a value of 100 has been assigned to the BAU alternative, while an IRR of 0% has been assigned to such scenario.

Qualitative evaluations of alternatives respect of level 2 criteria

The qualitative assessment of technical criteria such as commercial development, part-load efficiency and technical reliability has been done by considering the technical background of

Chapter 2. Considering the 1-9 Saaty scale (chapter 3), the evaluation of such criteria have been reported on Table 7.13.

Table 7.13: Qualitative assessment of technical sub-criteria

			Rating
Commercial Development	ICE + PV	FC + PV	9
Part-Load Efficiency	FC + PV	ICE + PV	5
Reliability	ICE + PV	FC +PV	1

Internal Combustion Engines have been present in the market from a long time, given its derivation from automotive industry, and its commercial development also led to a relevant diminishment in capital costs, as pointed out on Chapter 2. In this same chapter the part-load efficiencies have been reviewed for both plants, showing a better performance of FCs due to their modularity and different operating principles (chemical rather than oxidation process). Eventually, reliability of the two plants has been assessed. The lack of moving parts in FC system might suggest a better reliability of the latter, which is true on a general basis, as noted in chapter 2 when assessing the percentage of operating hours/total hours of the two systems. However, given the high maintenance costs of FC (almost double than ICEs) and the recent commercialization FC technology, an equal rate has been assigned for this factor.

Corporate/company's and facility manager's attitude towards alternatives has been considered by direct interviewing company's personnel, whose results are shown on Table 7.14.

Table 7.14: Qualitative assessment of social sub-criteria

			Rating
Corporate Attitude	ICE + PV	FC + PV	1/5
	ICE + PV	BAU	2
	FC + PV	BAU	7
Company's attitude	FC + PV	ICE + PV	1/3
	FC+PV	BAU	1
	ICE+PV	BAU	3
Facility Manager Attitude	ICE + PV	FC +PV	3
	ICE + PV	BAU	1/5
	FC + PV	BAU	1/3

Discussion with facility personnel led to a relevant interest by corporate policies in sustainable development policies, therefore solutions considering increased solar energy production (PV plant in the FC's solution is higher than ICE's one) and lower emissions, thus the rate of the former is strongly more important than the second (1/5 on inverse scale), with similar relevance of ICE+PV alternative and BAU alternatives, due to higher emissions, but increased PV energy production of the former. Company's attitude, in terms of General Manager opinion on the three solutions, led to a preference on economically sustainable, profits-producing and commercially available ICE plants, with indifference between BAU and FC plants. Eventually, Facility's Manager opinion has also been considered, which, given the variations in the productive cycle would rather prefer not to modify the productive system and would thus prefer the BAU scenario to both the ICE and FC solution.

7.5.2.3 Level 2 vs. Level 1 criteria

The comparison of level 2 vs. level 1 criteria encompasses the four main groups of the following sub-criteria assessment, namely social, economic, environmental and technological criteria. The rates reported on Table 7.15 have been used

Table 7.15: Qualitative assessment of environmental, economic and social criteria

		Rating
Human Health	Ecosystem Damage	3
Human Health	Resource Depletion	4
Human Health	CO2 emissions	5
Ecosystem Damage	Resource Depletion	2
Ecosystem Damage	CO2 emissions	3
Resource Depletion	CO2 emissions	3

		Rating
NPV	Capital Investment	1
NPV	Pay Back	1/3
NPV	IRR	5
Capital Investment	Pay Back	1
Capital Investment	IRR	5
Pay Back	IRR	5

		Rating
Reliability	Efficiency	3
Reliability	Commercial Development	1
Reliability	Partial Load Efficiency	7
Reliability	Loads Satisfied	1/3
Efficiency	Commercial Development	1
Efficiency	Partial Load Efficiency	5
Efficiency	Loads Satisfied	1/3
Commercial Development	Partial Load Efficiency	7
Commercial Development	Loads Satisfied	1/3
Partial Load Efficiency	Loads Satisfied	1/9

		Rating
Corporate Attitude	Company's attitude	1/5
Corporate Attitude	Facility Manager Attitude	1/3
Company's attitude	Facility Manager Attitude	3

A consistent hierarchy considering the environmental sub-criteria has been considered. Human Health impact has been considered as the most relevant priority, followed by ecosystem damage, CO_2 emissions and resource depletion. The economic criteria equally retain capital investment (minimized) and Net Present Value (maximized) as the most relevant criteria, followed by payback time and IRR values. From the technical viewpoint, satisfying company's loads represent the main priority, followed by plant reliability and efficiency, commercialization and part load efficiency. From the DM's perspective, the relevance of the DM process in the company's makes the general manager attitude as the most relevant in the decision making process, when referring to the specific issues in the company itself, followed by the facility's manager considerations.

7.5.2.4 Level 1 criteria vs. Main Goal

Eventually, in this last step the four criteria of the assessment have been benchmarked, compared to the final goal, i.e. choosing the best alternative for the company. Given the various scenarios which could have been chosen, three viewpoints have been selected:

- Techno-Economic Viewpoint;
- Environmental Viewpoint;
- Decisor Maker Viewpoint

The pair wise comparison, for each scenario, is shown on Table 7.16.

Table 7.16: Qualitative assessment of major criteria for selected scenarios

Techno-Economic Viewpoint

Technical	Economic	1
Technical	Environmental	9
Technical	Social	9
Social	Environmental	1
Social	Economic	1/9
Economic	Environmental	9

DM’s Viewpoint

Technical	Economic	1
Technical	Environmental	1
Technical	Social	1/9
Social	Environmental	9
Social	Economic	9
Economic	Environmental	1

Environmental Viewpoint

Technical	Economic	1
Technical	Environmental	1/9
Technical	Social	1
Social	Environmental	1/9
Social	Economic	1
Economic	Environmental	1/9

The evaluation of these three viewpoints has been done by assigning maximum weight (9 in the Saaty Scale) to the respective criteria in the three scenario, i.e. Techno-Economic for Scenario 1[7], DM for Scenario 2 and Environmental criteria for Scenario 3, while assigning equal weight to intra-criteria assessment (e.g. environmental and social criteria in Scenario 1). Furthermore, the scenario with equal weights to all the four criteria has been considered.

7.5.3 Results and Sensitivity Analysis

Alternatives have been evaluated by means of the hierarchic model and criteria previously presented. Results are shown on Figure 7.16, considering the three scenarios previously described, plus the equal-weights scenario. Combination of Internal Combustion Engine and PV plants results as the most preferred alternative for both the Techno-Economic and the DM’s viewpoint, mainly due to the economic performances (NPV, IRR and PB), and the commercial/technological reliability. From the environmental viewpoint, FC and PV plants resulted as the most-preferred solution, due to the low impact of FC plants and its high conversion efficiency, lowering fossil fuel consumption and increasing CO_2 emission reduction.

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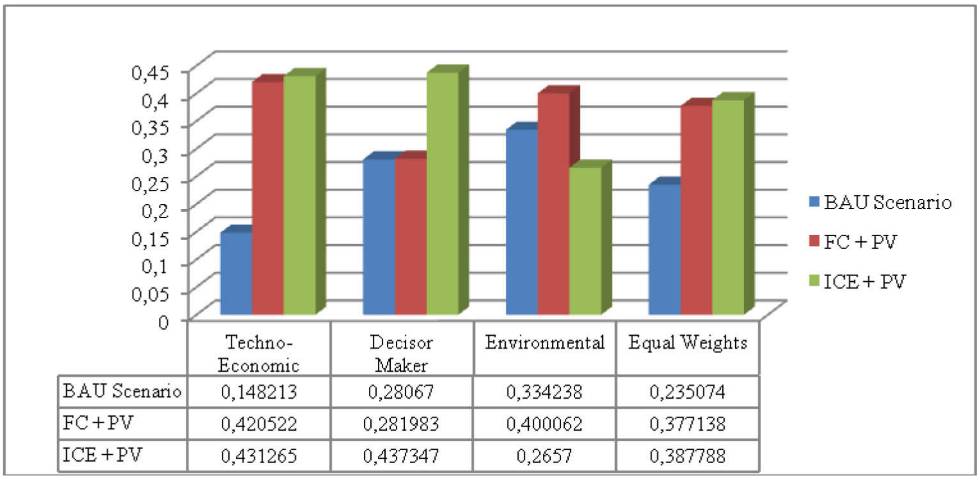
[7] Economic and Technical Criteria have been equally weighted (rating: 1) in Scenario 1.



	Techno-Economic	Decisor Maker	Environmental	Equal Weights
BAU Scenario	0,148213	0,28067	0,334238	0,235074
FC + PV	0,420522	0,281983	0,400062	0,377138
ICE + PV	0,431265	0,437347	0,2657	0,387788

Figure 7.16: Normal priorities for selected Scenarios

Interestingly, from both the Environmental viewpoint, the BAU scenario – i.e. maintaining the current situation – represents the second-preferred solution, due to the absence of capital investment – priority in the DM's perspective – and the low environmental performances of ICE solutions, featuring relevant emissions – especially of NOx and CO – higher than the base-scenario. An almost identical priority has been assigned to BAU and ICE scenario, with a minimal preference to the latter.

The equal-weights scenario presented similar results for ICE and FC plants – with a slightly higher performance of the former - while BAU scenario ranked far behind the CHP technologies. The solutions presented for the various scenario have been tested for eventual rank reversal problems (see Chapter 3). This has been done by deleting, for each scenario, the least-performing solution (BAU in Scenario 1, 2 and 4, FC+PV for Scenario 2), and assessing alternatives ranking, which are shown on Figure 7.17.

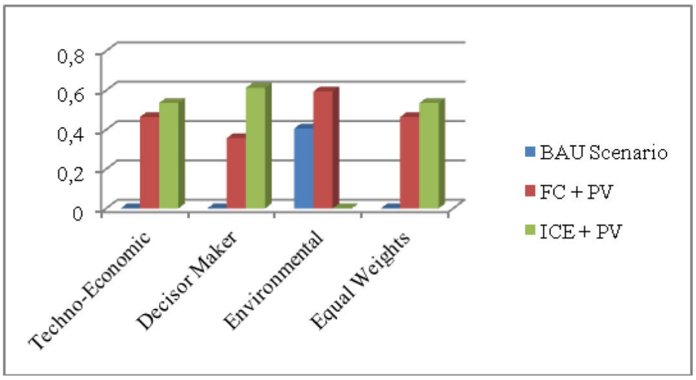
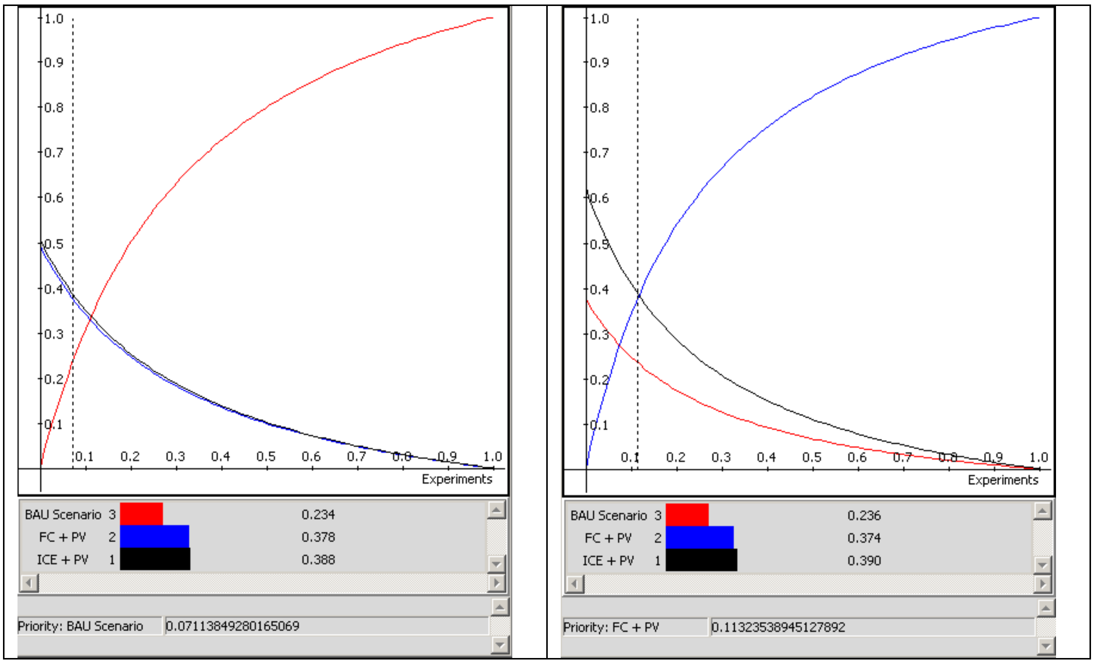


Figure 7.17: Normal priorities for selected Scenarios – Rank Reversal Test

As shown, no rank reversal occurred. For each scenario, the ranks among the alternatives have been maintained, with variations in the raw priorities value due to the occurred absence of one alternative which contributed to their calculation.

Sensitivity tests have been carried out in order to evaluate the robustness of the scenarios. Results, referred to the "Equal Weights" Scenario, are shown on Figure NUM, where the current situation (alternatives' priorities) is marked by the vertical dotted line. The graphs show the variations of final normal priorities of the alternatives depending on the variation of raw priorities of single alternatives, respectively BAU (a), FC+PV (b) and ICE+PV (c). The graphs are to be read in this fashion. Observing Figure 7.18a, a change in raw priority of BAU from 0.07 to 0.11 (cross between the red and the dotted black line) to 0.11 (red and blue line, value not reported in graph) makes this scenario more suitable than all the others. Thus a relevant variation is required (+57%), thus leading to a robust scenario when referring to BAU Alternative, which, given these considerations, it is unlikely to overcome all the others. Same computations, with similar results have been found out for FC and ICE solution, reported in Figure 7.18*b* and *c*. A slight increase in FC raw priority or a minimal dimishment of ICE's one (±4%) leads to an intersection and thus ranking's variation. Solution set is thus not robust.

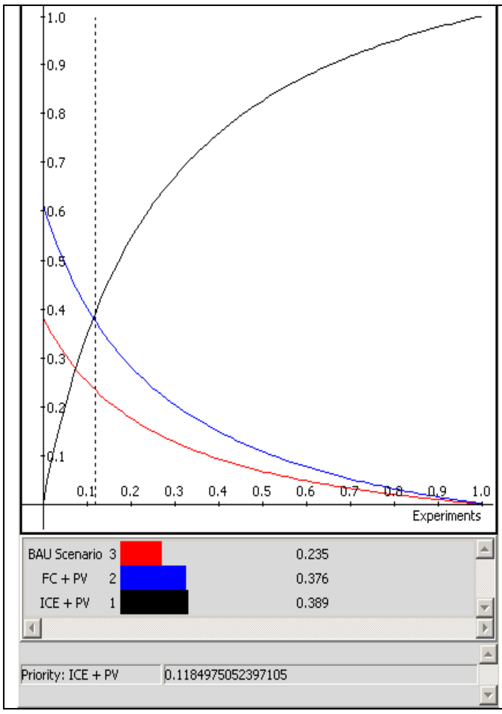


BAU Scenario 3 🟥 0.234
FC + PV 2 🟦 0.378
ICE + PV 1 ⬛ 0.388

Priority: BAU Scenario 0.07113849280165069

BAU Scenario 3 🟥 0.236
FC + PV 2 🟦 0.374
ICE + PV 1 ⬛ 0.390

Priority: FC + PV 0.11323538945127892



BAU Scenario 3 0.235
FC + PV 2 0.376
ICE + PV 1 0.389

Priority: ICE + PV 0.1184975052397105

Figure 7.18: Sensitivity analysis for Equal Weights scenario for BAU scenario (a), FC+FV (b) and ICE +PV (c)

8

Conclusions

The very concept of Sustainable Development (SD), from its most relevant conceptualization (WCED, 1987) to the most recent international conference of Durban (December 2011) encompasses multiple facets, referring to the so-called “three pillars” (Adams, 2006) of SD. The complex task of Sustainable Energy Plant Design has been addressed in this work.

The decision making process flows from the preliminary, analytical assessment to a more practical, creative phase of alternatives identification, ending up with a choosing stage for finally selecting one of the alternatives. However, traditional multi-criteria models separately considers multi-optima simulation and multi-attribute decision making support, using the former in advanced design process, while limiting the latter for picking up the alternatives from a pre-determined basket of solutions.

The primary innovation of this work is represented by the combination of Multi-Objective and Multi-Attribute analysis for supporting the decision making process, namely referring to the “Design” and the “Choice” stages of the latter, as represented on Figure 8.8.1.

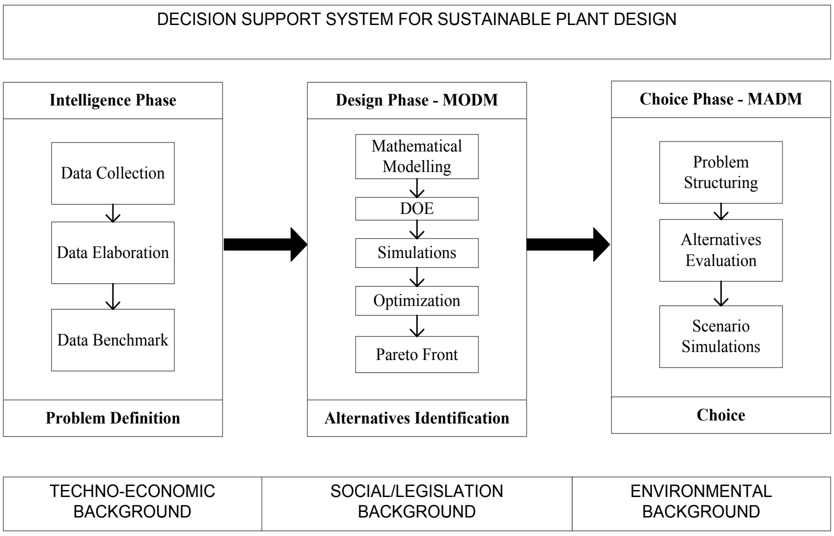


Figure 8.8.1: DSS for sustainable Plant Design

At the very bottom of the methodology, the triple-line of SD has been considered, with specific reference to Combined Heating and Power (CHP) plants, together with Photovoltaics solutions (PV). Referring to technical and economic characterization of the latter, a comprehensive literature study has identified equipment costs curves depending on plant size for the following technologies:

- Internal Combustion Engine (ICE), gas- or liquid-fuelled;
- Medium/Large Sized fixed-speed Gas Turbines (GT);
- Micro-Turbines, gas-fuelled (MT);
- Fuel-Cells, gas fuelled (FC).

Eventually, given the relevance and flexibility, Photovoltaics Plants (PV) has been added to the research study. Capital Investment Cost curves, as reviewed in chapter 2, for CHP technologies are reported in the following graph, also useful for assessing size single plant availability (in terms of maximum power size) of each installation, while current PV plant costs amount to about 3000-3300 €/kW$_p$.

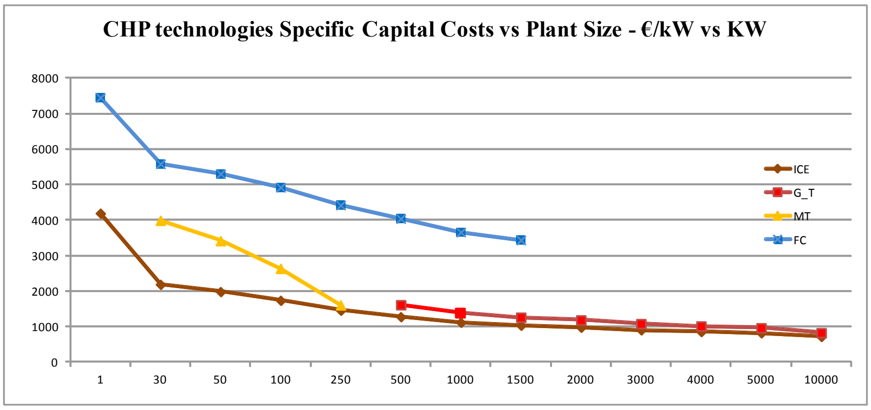


Figure 8.1.2: CHP Specific Investment Costs Curves

Among the operating costs, other than fuel costs, maintenance often results as a decisive factor in CHP plant design, therefore full-contract maintenance costs have been assessed and reviewed, as summarized on Figure 8.1.3.

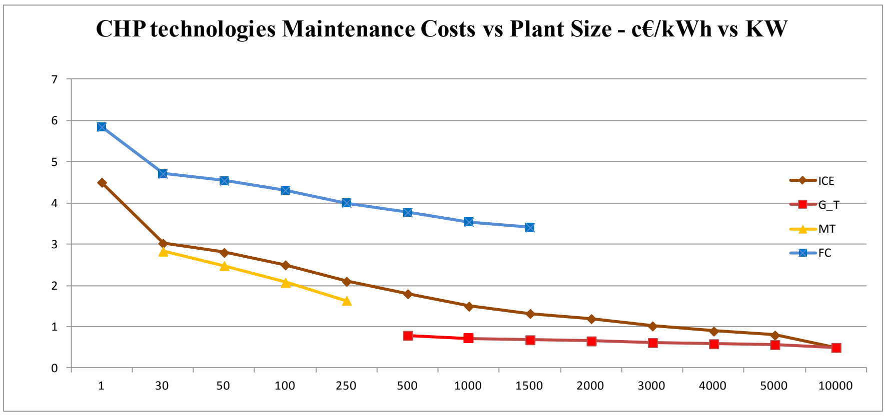
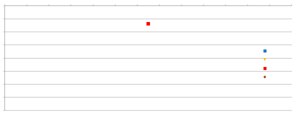


Figure 8.1.3: CHP specific maintenance cost curves

Referring to environmental impact assessment, a choice has been made by excluding, at least in the first part of the assessment, the consideration of CO_2 emissions, given that, by most of the academic literature, this value is considered as the only environmental factor to be considered in the optimization modeling, while a broader range of pollutants are required to be monitored by the regulator. Each of the technologies presents a different emission factor, in terms of grams of pollutants per input energy. Technologies characterization from US-EPA standards and documentation are summarized on Figure 8.1.4.



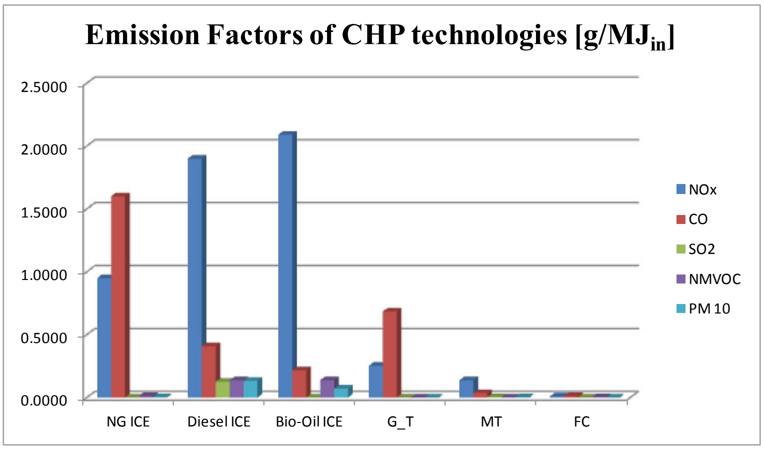


Figure 8.1.4: CHP emission factors

Furthermore, the relative relevance of each pollutant had to be considered. For this purpose, the methodology of the Life Cycle Assessment has been used. Specifically a sub-stage of the latter, i.e. the Life Cycle Impact Assessment, has been used for assessing the impact on "Human Health" of CHP's emissions. The methodology "Eco-Indicator 99" utilizing the USES-LCA method using data from World Health Organization, identifies the relative impact of pollutants emissions, expressed in "Disability Adjusted Lifetime Years" (DALY) per kg as proposed by the method, and reported on Figure 8.1.5.

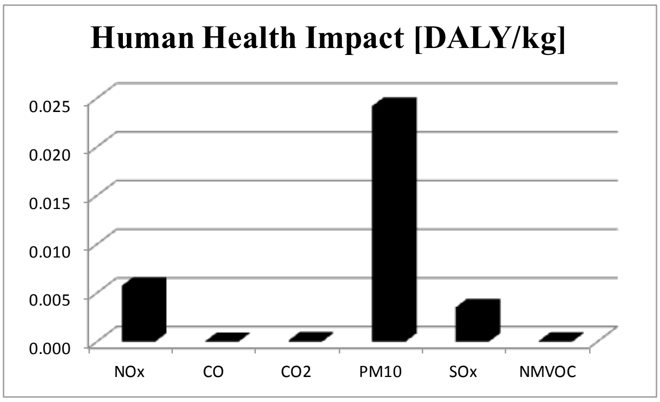


Figure 8.1.5: Human Health Impact Factor of some macro-toxicants

Eventually, the normative background strictly depends on at least country-specific conditions. The National (Italian) policies follows the International and – most relevantly – the European regulatory framework regarding the legislation, with a triple aim of promoting renewable energy use, pollutants reduction and energy efficiency. For these purposes, a broad range of incentives have been developed throughout the years, diversified for fuel source, fuel usage and technology, which are summarized, and quantified for the National scenario, in Figure 8.1.6.

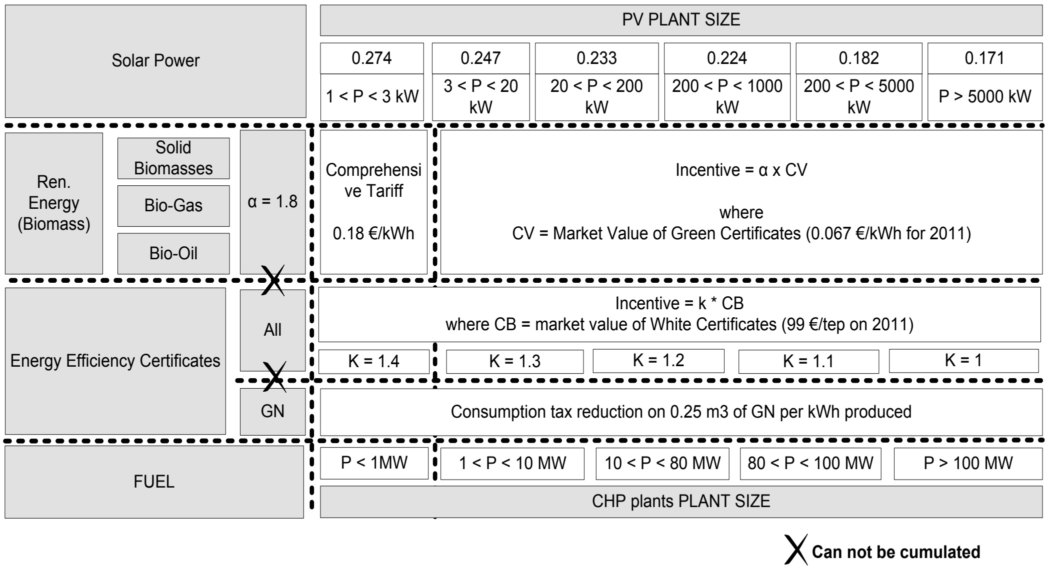


Figure 8.1.6: Italian Legislative Framework on considered CHP and PV technologies

A complex scenario is thus presented when having to design CHP and PV plants, with varying objectives both economic and environmental. A two-step approach for alternative identification and choice is presented in this methodology.

A model for multi-objective optimization is presented on Chapter 3, using the following objective functions:

$$\mathrm{Max(NPV)} \qquad (8.1)$$

$$\mathrm{Max(TEIR)} \qquad (8.2)$$

Where NPV represents the sum of the cash flows (ACF), actualized and considered throughout the whole duration of the investment (*y*), on monthly basis (*m*) for each of the technologies assessed (*t*) consisting in actualized revenues (TAR) and costs (TAC), in turn depending on revenues from selling exceeding (R^{exc}) power, avoided purchasing of electricity and heat (R^{av}), incentives (I) and variable costs such fuel consumption (C^f), maintenance (C^m), heat and power integration (C^{int}) and excessive heat disposal(C^{exc}).

$$NPV + I_o = \sum_{y=0}^{15} \overline{ACF}_y = \sum_{y=0}^{15}\left(\overline{TAR}_y - \overline{TAC}_y\right) = \sum_y \sum_m \sum_t \left(\overline{R}_{el}^{exc} + \overline{R}_{el}^{av} + \overline{R}_h^{av} + \overline{I}\right)_{y,m,t} - \sum_y \sum_m \sum_t \left(C^f + C^m + C_{el}^{int} + C_h^{int} + C_h^{exc}\right)_{y,m,t} \qquad (8.3)$$

Total environmental impact reduction (TEIR), has been calculated as a sum of impacts from avoided emissions from electricity production (AEI_e, positive), avoided emissions from heat production (AEI_h positive) and current emissions of the simulated design (negative, CEI) each of the emission considering the relative specific impact factor (IF) in terms of human health impact assessment of each pollutant *p* as previously presented in relation to human health impact.

$$TEIR = AEI_e + AEI_h - CEI =$$
$$\sum_{p=1}^{5} EL \cdot ER_p^{el} \cdot IF_p + \sum_{p=1}^{5} E_{h,m}^{req} \cdot ER_p^{h} \cdot IF_p - \sum_{p=1}^{5} \sum_{t=1}^{7} FC_t \cdot ER_{t,p} \cdot IF_p \qquad (8.4)$$

At this stage of the assessment, CO_2 has been excluded from the optimal design process. The choice has been made due to the fact that CO_2 emissions, while impacting on a global level, on a local level by far minor when compared to other larger natural and anthropogenic sources, while local impact of pollutants such as NO_x, PM,. SO_x, CO and VOCs is highly more relevant on a local scale, thus it has been considered to focus the Multi-Objective analysis on the latter.

Eventually, the optimization model has been adapted to site-specific conditions (energy and heat demands, available roof area, solar radiation) and subjected to some constraints in order to promote correct plant sizing (avoiding excessive heat wasted), satisfying the highest percentage of company's heating and power needs and respect site-specific limits (e.g. available roof area).

The simulations, combining Microsoft Excel^{TM} worksheet for flexible modeling and Esteco ModeFrontier^{TM} for scheduling and optimization, runs on iterative procedures in order to identify the Pareto Front, i.e. the group of non-dominated solutions, defined as the solutions which cannot be improved in one of the two objectives without worsening the other. The model has been applied to CHP plant design in various contexts, related to the health care and the manufacturing industry. Results, expectedly, strongly differs due to site-specific conditions and energy demand structure. For each of the case studies, a standard analytic framework of the Pareto Front has been considered, in order to identify both profitable and/or environmental friendly solutions. An example of Pareto Front determination process done by ModeFrontier is reported in Figure 8.1.7 , which is the one of the Front in a case studied in this work.

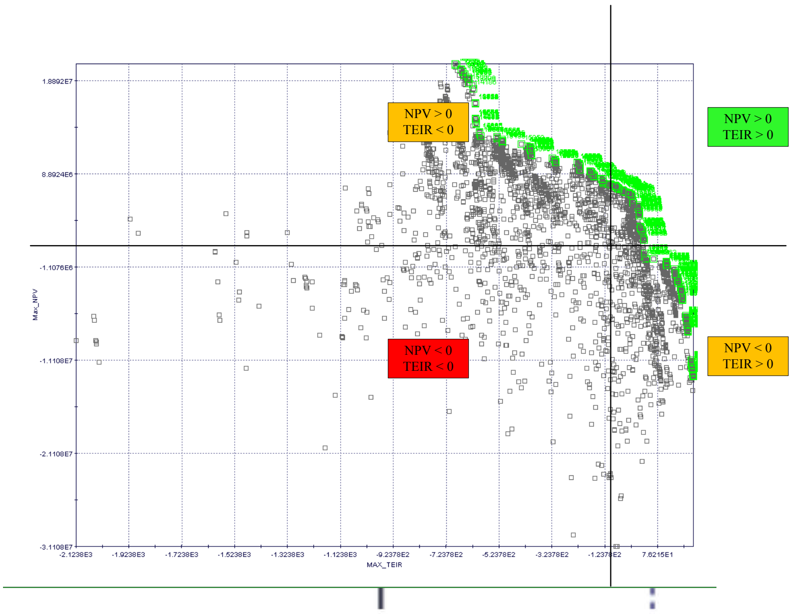


Figure 8.1.7: Mode Frontier identification process of a Pareto front

The third and last step of the methodology consisted in applying a Multi-Attribute decision making method for selecting the most appropriate alternative among the feasible ones previously identified. The strength of this step relies in the flexibility of adapting the decision support method to customer-specific assessment.

In chapter 8, a comprehensive assessment regarded the evaluation of a complex Industrial Area located in Perth, Western Australia, specifically assessing its environmental impact in terms of LCA of its air and water emissions. Methodology for multi-optima design of CHP plant (Chapter 3) has been applied to the case study of one of the companies in the Industrial Area, allowing identifying both economic-profitable and environmental-friendly alternatives. The evolution of the Pareto front, for the base scenario, is represented on Figure 8.1.8.

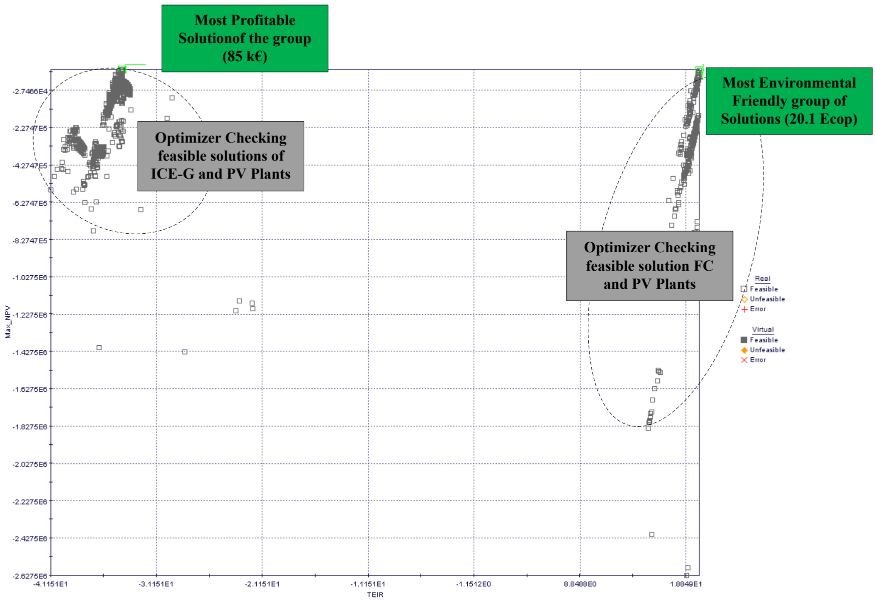


Figure 8.1.8:Pareto Front for the Company, Scenario 1, details

Two main groups of solutions have been found by the simulator, which have been later on compared by using the AHP methodology, allowing considering a broader range of criteria, without limiting the analysis on only the NPV and the Human Health Impact assessment as done in stage 2.

The structure of the AHP model is reported on Figure 8.1.9, and takes into consideration both quantifiable (Efficiencies, Capital Investment, CO_2 emissions, ecc.) and non-quantifiable factors (commercial development, technological reliability, company's attitude, ecc.).

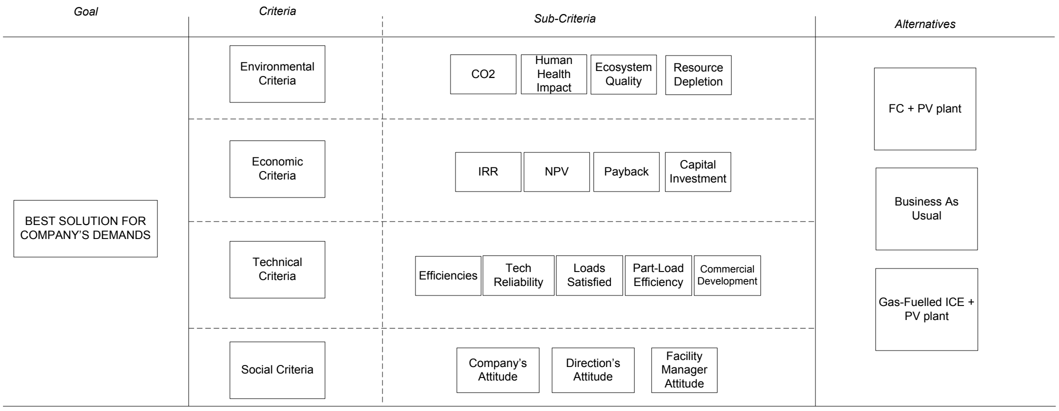
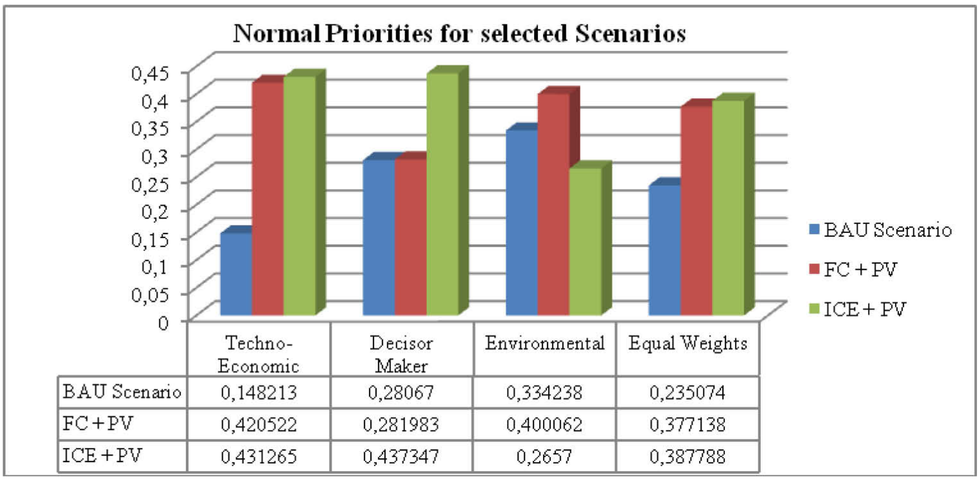


Figure 8.1.9:AHP structure of a case study

Alternatives benchmark has been done by selecting three main scenarios, the latter varying the ratings – and thus the weights – of each main criteria (economic, environmental, social and technical). Three main viewpoints have been considered, i.e.:

- Techno-Economic Viewpoint: focusing on both maximizing economic (maximizing profits and profitability while minimizing capital investment and payback) and technical (loads satisfied, efficiencies, reliability and commercial development) criteria;
- Environmental Viewpoint, considering pollutants emissions (CO_2) and impact (both on human health and ecosystem), together with fossil resource depletion, as the main criteria overcoming all the others;
- Decision Making Viewpoint, considering DM's viewpoints, both on a corporate, company's and facility manager's level, as the main criteria.

Equal weights scenario has also been considered. The pair wise comparison of the three alternatives led to the results shown on Figure 8.1.10.



	Techno-Economic	Decisor Maker	Environmental	Equal Weights
BAU Scenario	0,148213	0,28067	0,334238	0,235074
FC+PV	0,420522	0,281983	0,400062	0,377138
ICE+PV	0,431265	0,437347	0,2657	0,387788

Figure 8.1.10:Priority of selected alternatives for the case study

Combination of Internal Combustion Engine and PV plants results as the most preferred alternative for both the Techno-Economic and the DM's viewpoint, mainly due to the economic performances (NPV, IRR and PB), and the commercial/technological reliability. From the environmental viewpoint, FC and PV plants resulted as the most-preferred solution, due to the low impact of FC plants and its high conversion efficiency-

Interestingly, from both the DM and the Environmental viewpoint, the BAU scenario – i.e. maintaining the current situation – represents the second-preferred solution, due to the absence of capital investment – priority in the DM's perspective – and the low environmental performances of ICE solutions, featuring relevant emissions – especially of NOx and CO – higher than the base-scenario.

The combination of Multi-Objective and Multi-Attribute decision making allowed a comprehensive solution of the decision making process, allowing both identification of a range of feasible, trade-off, solutions – the Pareto Front – and permitting to include a broader range of factors in the following stages of the assessment, during which the AHP methodology proved to be an easy, structured and comprehensive methodology for assisting the DM process.

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Appendix

Appendix A

Life-Cycle Impact Assessment Methodologies

Name	Developed by	Type	Advantages and limitations
CML	Environmental Centre of Leiden University (DE), 2001	Multi problem-oriented	Multiple categories considered, but absence of a unique indicator. Normalization factors depending on the specific geographical location. Damage categories considered are: acidification, climate change, eutrophication, Ecotoxicity, human toxicity, land use, photochemical oxidation, abiotic resource depletion, ozone depletion, ionizing radiations.
CERA (Cumulative Energy Requirement Analysis	Hancock (1978) e Pimentel (1973)	Single problem oriented	It limits the analysis to the energy issues, referring to direct (fuel consumption) and indirect (material extraction) energy use, with sub-categories depending on specific fuel to be used and material extracted.
CExD (Cumulative Exergy Demand Analysis)	Boesch et al., 2007	Single oriented problem;	Similar to CERA, but considering the exergetic value of the resources (fixing reference temperatures) and considering other impacts such as water usage, metals and minerals.
Ecosystem Damage Potential (EDP)	Koellnerr e Scholz (2007)	Single damage oriented	Ecosystem quality is consideradly the method, intended as land occupation and transformation. 53 types of land and 6 occupation classes have been considered. Biodiversity is also taken into consideration.
IPCC 2001	IPCC 1997, 2001	Single problem oriented	Reference model for climate change GHG emissions, used also inside other methodologies for global warming impact calculation. Temporal horizon of 20, 50 and 100 years.
TRACI	US-EPA, 2002	Multi problem oriented	Impacts are calculated using US reference values. Categories identified are ozone depletion, global warming, eutrophication, photochemical oxidation, human health, fossil fuel usage and land use.

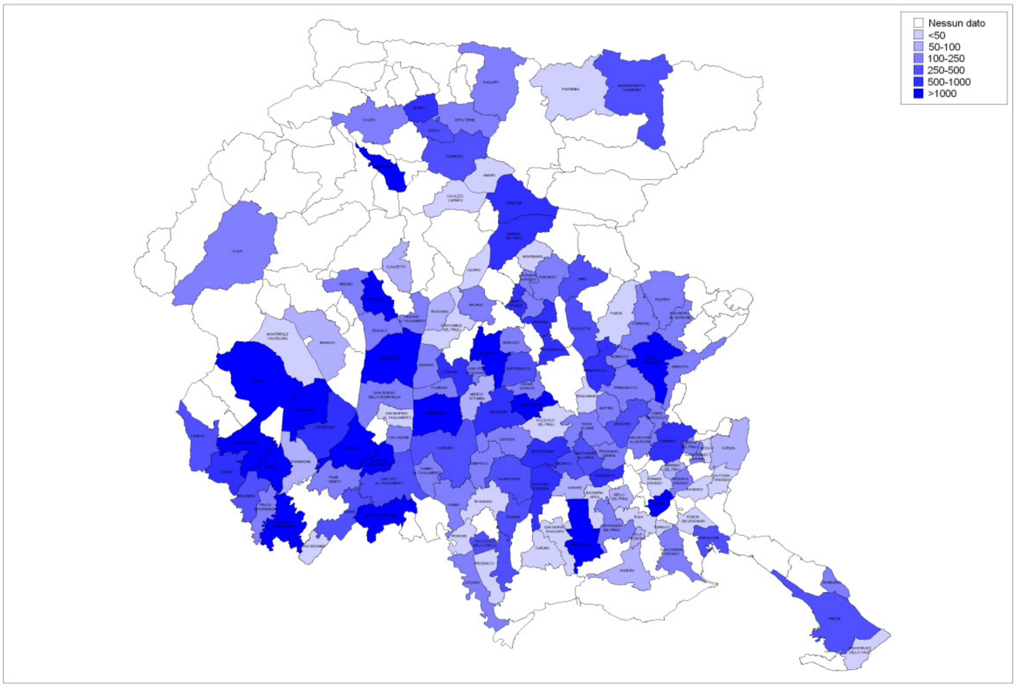
Name	Developed by	Type	Advantages and limitations
ECO-Indicator 99	Goedkoop e Spriensma, 1999	Multi-problem, multi damage, single score method.	Multiple categories are referred to three main typologies of damage, that is human health, ecosystem damage and resource consumption. In the first category carcinogens emissions, climate change, ionizing radiation, ozone depletion, respiratory effects are considered. Ecosystem damage considers acification/eutrophication effects, Ecotoxicity and land occupation while resource consumption considers both fossil and mineral resources. Normalization step is taken considered regional values, while weighing is done using one of three perspectives (Egalitarian, Individualist or Hierarchical) each one considering different damage categories..
Ecological Footprint (EF)	Huijbregts et al. 2006	Single problem-oriented	Only resource consumption is taken into consideration, considering the land biologically productive and water needed by a consuming population and in order to absorb the wastes generated due to fossil fuel consumption, indirect emissions and nuclear waste.
Ecological Scarcity	Brand et al. (1998)	Multi-problem oriented	Weighting and aggregation of different impacts considering ‘ecofactors’, calculated from the current pollution level and a critical one. Impacts considered are air emissions, superficial and ground water, waste and consumed resources.

Name	Developed by	Type	Advantages and limitations
EDIP 97 (Environmental Design of Industrial Products)	Danish LCA Center (1997)	Multi-damage oriented	The method considers impacts similarly to Eco-Indicator or CML, accounting for various categories(resources, environmental and working impact) normalizing by a geographical reference value and differently weighting the categories.
EDIP 2003	Danish LCA Center (2003)	Multi-damage oriented	Evolution of the previous method, with more categories such as acidification, eutrophication, ozone exposition, human toxicity and eco-toxicity.
EPS 2000 (Environmental Priority Strategy)	Ryding e Steen, 1991	Multi-damage oriented	It considers the specific impact on some subjects such as biodiversity, industrial production, human health, resources and aesthetic value, calculated an environmental burden express as 'willingness to pay' (Environmental Load Unit). Developed in industrial decision support framework.
IMPACT 2002	Swiss Federal Institute of Technology, 2002	Multi-problem multi-damage oriented	Similarly to EcoIndicator 1999, it considers 14 impact categories (human toxicity, respiratory effects, ionizing radiations, ozone depletion, photo-chemical oxidation, water eco-toxicity, acidification and eutrophication, global warming, non-renewable resource use) in turn categorized in four damage categories (human health, ecosystem quality, climate change and resource consumption).

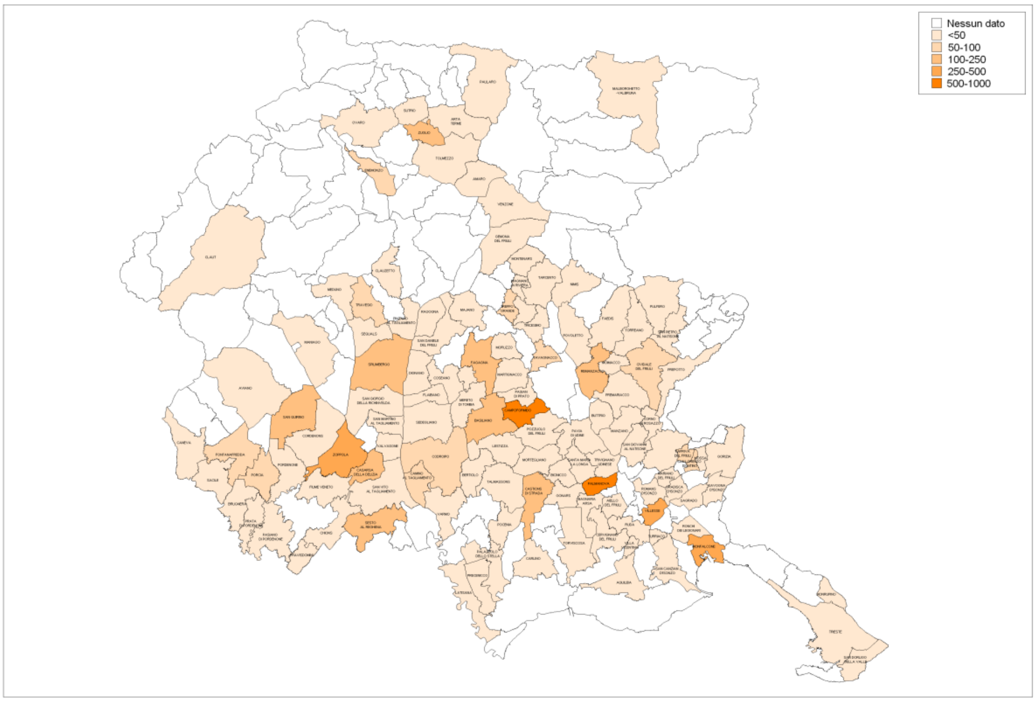
Appendix B

DSS for regional planning: GIS Mapping

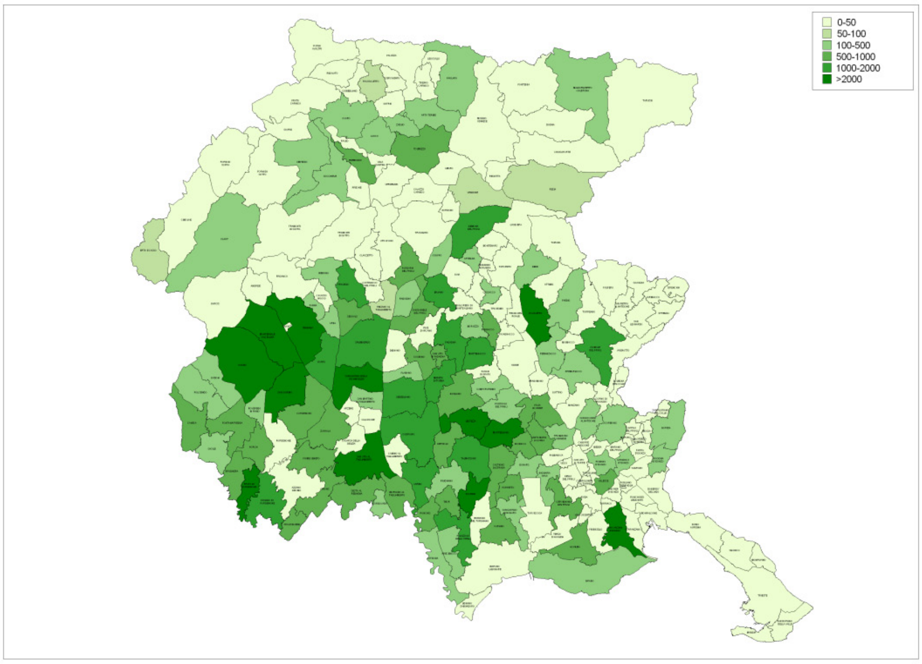
Total MWh consumption of FVG primary industry on municipal basis



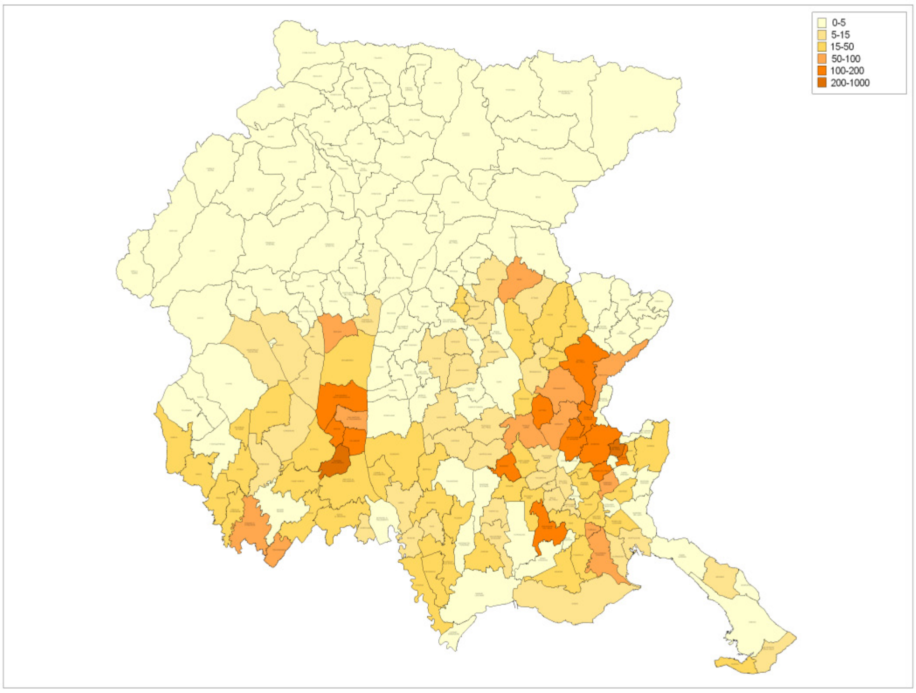
Energy intensity (MWh/km2) demands of total primary industry;



Total Energy (MWh) producible from zoo technical residues anaerobic digestion

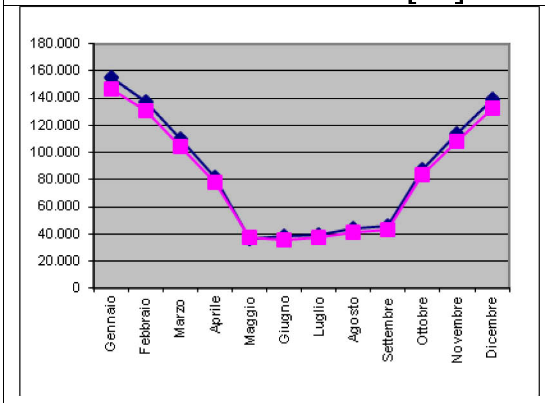
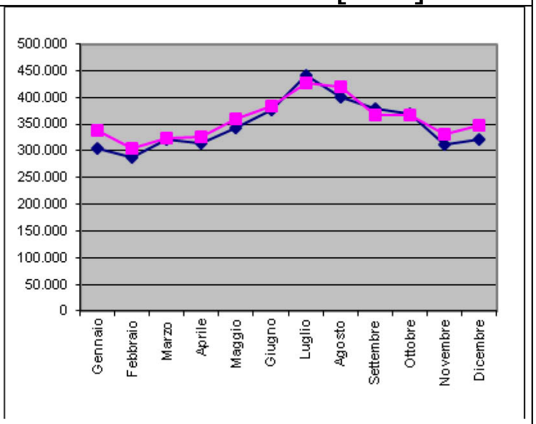


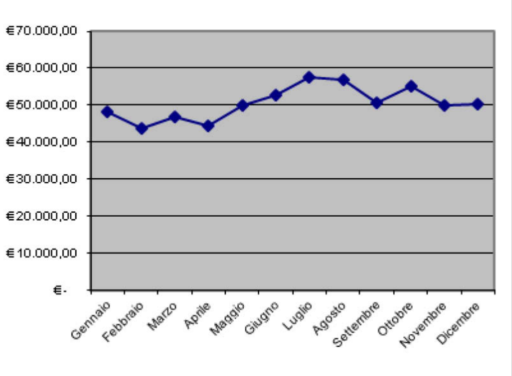
Energy intensity (MWh/km2) producible from grapes production on municipal basis



Appendix C

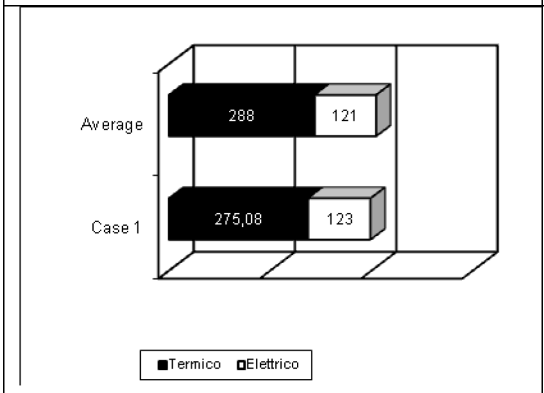
DSS for health-care: data on surveyed structures

<table>
<tr><th colspan="2">CASE 1</th></tr>
<tr><td>BUILDING DATA
Beds: 350
Heated Area: 34.953 m^2
Volume: 95.435 m^3
Degree Days: 2.544</td><td>PLANT DATA
Primary Fuel: Natural Gas
Heat Power Installed: 5,8 MW
Power Installed: 0,75 MW</td></tr>
<tr><td>DATI AGRREGATI DI CONSUMO
Natural Gas 2006: 1.027.866 m^3
Natural Gas 2007: 977.779 m^3
Power 2006: 4.171.323 kWh
Power 2007: 4.292.172 kWh</td><td>Other Data
Chilling Power: 4,4 MW
Power Factor: 0,97</td></tr>
<tr><td colspan="2">Gas and Power Monthly Trends:</td></tr>
<tr><td>Natural Gas 2006/2007 [m^3]</td><td>Power 2006/2007 [kWh]</td></tr>
<tr><td> </td><td> </td></tr>
<tr><td>Gas Costs 2006/2007</td><td>Power Costs 2007</td></tr>
</table>

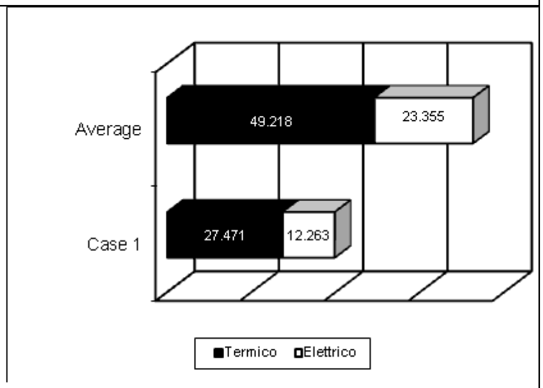
n.a.	€70.000,00 €60.000,00 €50.000,00 €40.000,00 €30.000,00 €20.000,00 €10.000,00 €- Gennaio Febbraio Marzo Aprile Maggio Giugno Luglio Agosto Settembre Ottobre Novembre Dicembre

Primary Indicators

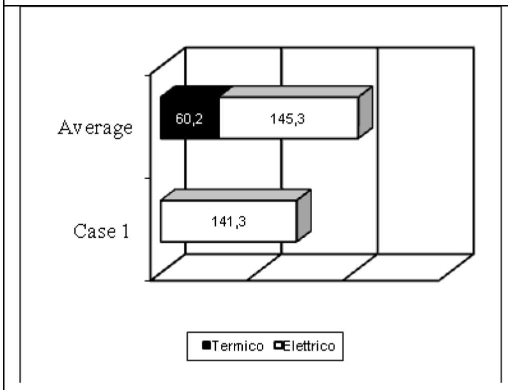
kWh/m^2



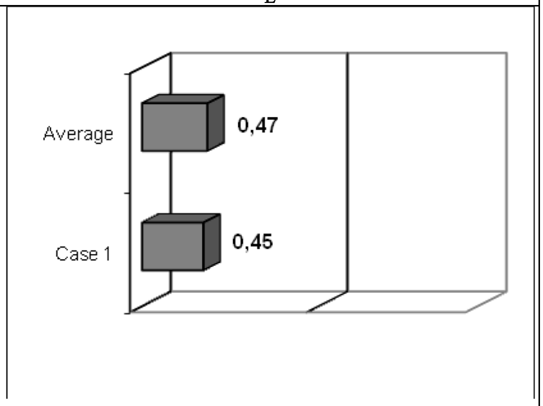
kWh/P.L.



€/MWh



I_E

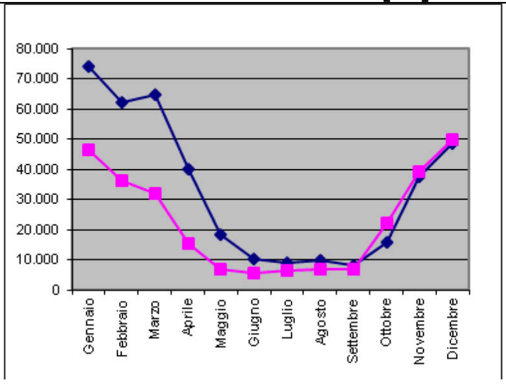


CASE 2

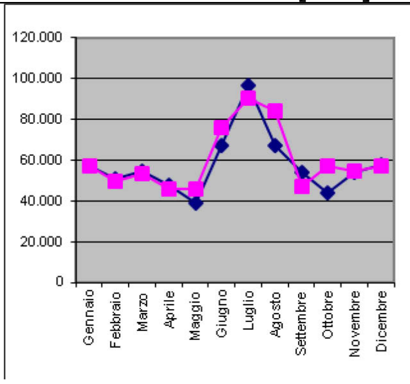
BUILDING DATA Beds: 105 Heated Area: 10.571 m^2 Volume: 37.000 m^3 Degree Days: 2.283	**PLANT DATA** Primary Fuel: Gas Natural Heat Power Installed: 2 MW Power Installed: 2 MW
CONSUMPTION DATA Natural Gas 2006: 397.890 m^3 Natural Gas 2007: 274.206 m^3 Power 2006: 689.685 kWh Power 2007: 716.617 kWh	**OTHER DATA** Chilling Power Installed: n.d. Power Factor: 0,7957

Gas and Power Trends

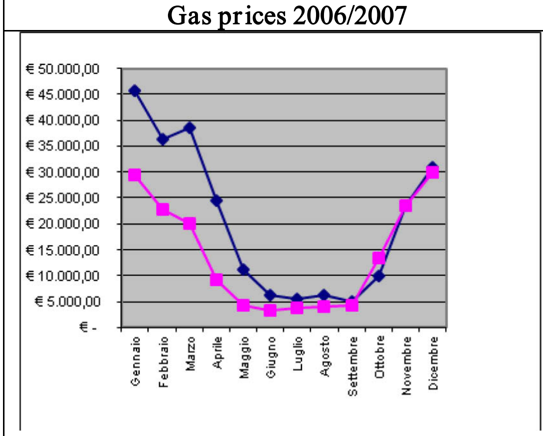
Natural Gas 2006/2007 [m^3]



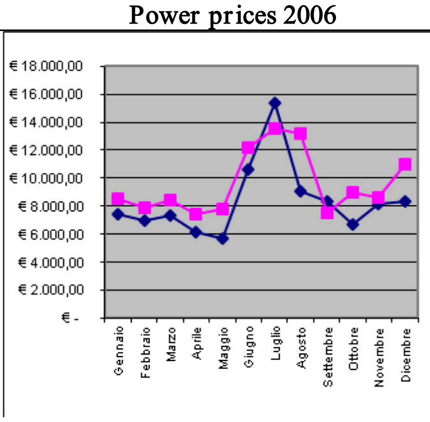
Power 2006/2007 [kWh]



Gas prices 2006/2007



Power prices 2006



<table>
<tr><th colspan="2">Primary Indicators</th></tr>
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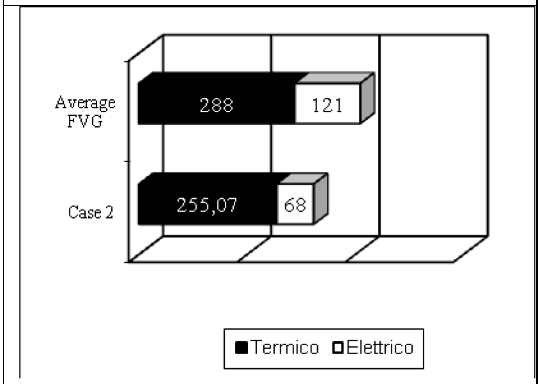

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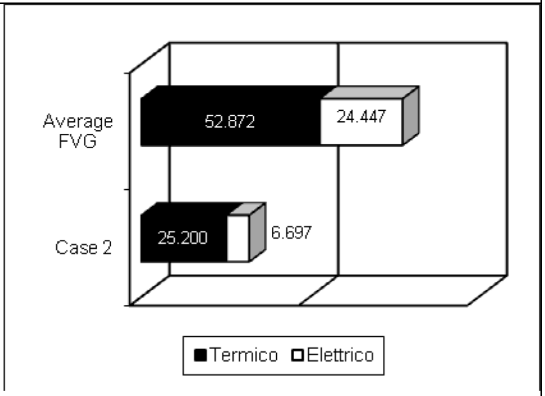

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<tr><th>€/MWh</th><th>I_E</th></tr>
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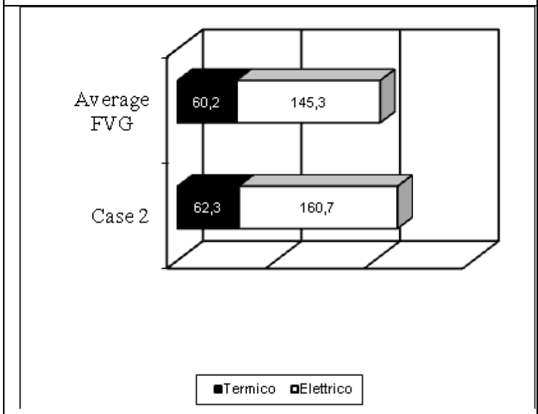

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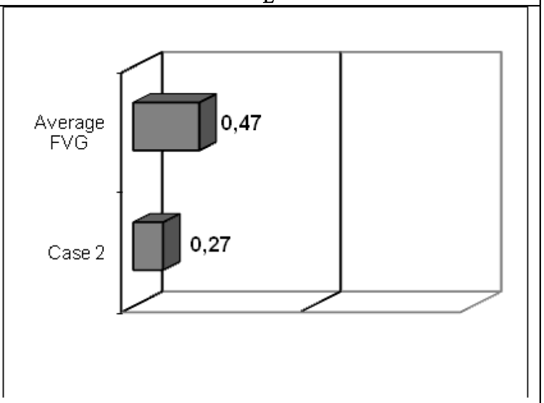

</td></tr>
</table>

Appendix D

LCI of Kwinana Industrial Area emissions

Substances	**AIR [kg]**	**WATER [kg]**	**LAND [kg]**
1,2-Dibromoethane	1.58	-	-
1,3-Butadiene (vinyl ethylene)	204.01	-	-
Acetaldehyde	16,040.17	-	-
Acetone	25,008.90	-	-
Acrylamide	280.61	-	-
Acrylic acid	355.05	-	-
Ammonia (total)	1,713,545.08	28,155.94	396.99
Antimony & compounds	7.67	-	2.35
Arsenic & compounds	105.15	22.32	341.69
Benzene	3,567.70	-	6.83
Beryllium & compounds	8.90	0.53	-
Biphenyl (1,1-biphenyl)	-	-	-
Boron & compounds	2.40	460,000.00	-
Cadmium & compounds	65.30	7.80	1.01
Carbon Dioxide	-	-	-
Carbon disulfide	28,161.97	-	-
Carbon monoxide	6,737,413.03	-	-
Chlorine & compounds	3,275.74	-	-
Chromium (III) compounds	260.53	13.60	2.45
Chromium (VI) compounds	29.57	0.01	0.05
Cobalt & compounds	3.43	2.47	4.24
Copper & compounds	102.97	392.06	15.13
Cumene (1-methylethylbenzene)	364.56	-	17.54
Cyanide (inorganic) compounds	4,272.05	-	0.02
Cyclohexane	15,681.50	-	21.91
Ethanol	955.00	-	-
Ethylbenzene	1,517.72	-	39.43
Fluoride compounds	48,175.00	78,784.88	236.93
Formaldehyde (methyl aldehyde)	38,645.71	-	-
Glutaraldehyde	4.47	-	-
Hydrochloric acid	365,008.92	-	928.80
Hydrogen sulfide	26,434.21	-	-
Lead & compounds	106.99	5.80	3.96
Magnesium oxide fume	-	-	-
Manganese & compounds	585.64	1,864.62	197.36
Mercury & compounds	313.30	0.33	4.81
n-Hexane	27,503.10	-	2.48
Nickel & compounds	1,229.78	12.22	6.17
Nickel carbonyl	-	-	-
Nickel subsulfide	603.30	-	-
Nitric acid	-	-	-
Oxides of Nitrogen	8,322,066.17	-	-
Particulate Matter 10.0 um	971,234.46	-	-
Particulate Matter 2.5 um	251,933.65	-	-
Phenol	10.87	10.02	-
Polychlorinated dioxins and furans (TEQ)	0.00	-	-
Polycyclic aromatic hydrocarbons (B[a]Peq)	219.59	-	21.26
Selenium & compounds	99.35	5.77	1.68

Substances	**AIR [kg]**	**WATER [kg]**	**LAND [kg]**
Styrene (ethenylbenzene)	91.41	-	-
Sulfur dioxide	10,000,868.19	-	-
Sulfuric acid	251.18	-	-
Toluene (methylbenzene)	16,196.11	-	259.47
Total Nitrogen	-	41,762.31	-
Total Phosphorus	-	5,087.00	-
Total Volatile Organic Compounds	2,131,906.49	-	-
Xylenes (individual or mixed isomers)	9,078.71	-	256.33
Zinc and compounds	595.01	81.52	127.31
Total	30,764,392.20	616,209.18	2,896.20